PHOTOISOMERIZATIONS OF CYCLOHEPTA-2,4-DIENONES

PHOTOISOMERIZATIONS OF CYCLOHEPTA-2,4-DIENONES

By

KENNETH ERNEST HINE, B.Sc.

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Doctor of Philosophy

McMaster University
August 1973

DOCTOR OF PHILOSOPHY (1973)
(Chemistry)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Photoisomerizations of Cyclohepta-2,4-dienones

AUTHOR: Kenneth Ernest Hine, B.Sc. (McMaster)

SUPERVISOR: Professor R. F. Childs

NUMBER OF PAGES: xiv, 193

SCOPE AND CONTENTS:

This thesis has resolved some rather fundamental and rudimentary questions concerning the photochemistry of cyclohepta-2,4-dienones.

A new approach has been taken to assess the role of (π,π^*) excited states in the photoisomerizations of 2,6,6-trimethylcyclohepta-2,4-dienone, eucarvone. It involved an investigation of the low temperature photorearrangements of protonated eucarvone in fluorosulphuric acid. The results, in addition to those obtained from a re-examination of neutral eucarvone photochemistry, have demonstrated that both (n,π^*) and (π,π^*) states are involved in the formation of primary photoproducts. A scheme has been formulated which relates these products to these excited states.

An investigation of the photoisomerizations of cyclohepta-2,4-dienone and 2-methylcyclohepta-2,4-dienone has revealed that substituents have a profound influence upon the mode of reaction of the (π,π^*) states of this dienone system. Whereas eucarvone was found to produce

3,7,7-trimethylbicyclo[4.1.0]hept-2-en-4-one from this state, the less substituted systems yielded only bicyclo [2.2.1]hept-2-en-7-ones. This substituent effect has been interpreted mechanistically in terms of an intermediate in the eucarvone reaction in which positive charge is developed upon the carbon bearing the two methyl groups.

A novel synthesis of cyclohepta-2,4-dienone has been developed which involved as the key step the thermal isomerization of protonated cyclohepta-3,5-dienone.

to my parents, and my wife Lorraine

ACKNOWLEDGEMENTS

I would like to sincerely thank my supervisor, Professor R. F. Childs, for his knowledgeable advice, critical appraisal, and continuous enthusiasm throughout this work. Also, I am indebted to the members of our research group for their help and friendly cooperation.

I wish to extend my thanks to Mr. Brian Sayer for running all the 100 MHz pmr spectra, to Messrs. Claus Schonfeld and Ian Thompson for technical advice, and to Mrs. Lillian Anne Giavedoni who typed the manuscript.

I would especially like to thank my wife Lorraine for her patience and understanding during the course of this work.

TABLE OF CONTENTS

Table of Contents (cont'd)

Table of Contents (cont'd)

Table of Contents (cont'd)

LIST OF FIGURES

List of Figures (cont'd)

List of Figures (cont'd)

LIST OF TABLES

List of Tables (cont'd)

PART I. INTRODUCTION

INTRODUCTION

Since earliest times man has had an irresistible urge to carefully define and categorize every object within his reach. As he progressed, the development of more refined probes increased his sphere of influence. The telescope penetrated the heavens in search of other celestial bodies; the microscope invaded the private world of unicellular creatures with their system of organelles. Rapid technological advances during the last century, no doubt abetted by the wars of 1914 and 1939, have permitted the investigation of subcellular species. Many branches of science now respond to man's insatiable desire to study properties of atoms and molecules and nowhere is man's inherent penchant for organization more evident.

This thesis records the results of an investigation which has resolved some of the fundamental questions concerning the photochemistry of 2,6,6-trimethylcyclohepta-2,4-dienone, eucarvone. A new approach has been taken to evaluate the role of (π,π^*) excited states which involves the study of the photorearrangements of protonated eucarvone. The introduction describes this approach in a general sense and examines some basic principles involved in photoisomerizations of unsaturated ketones and protonated ketones.

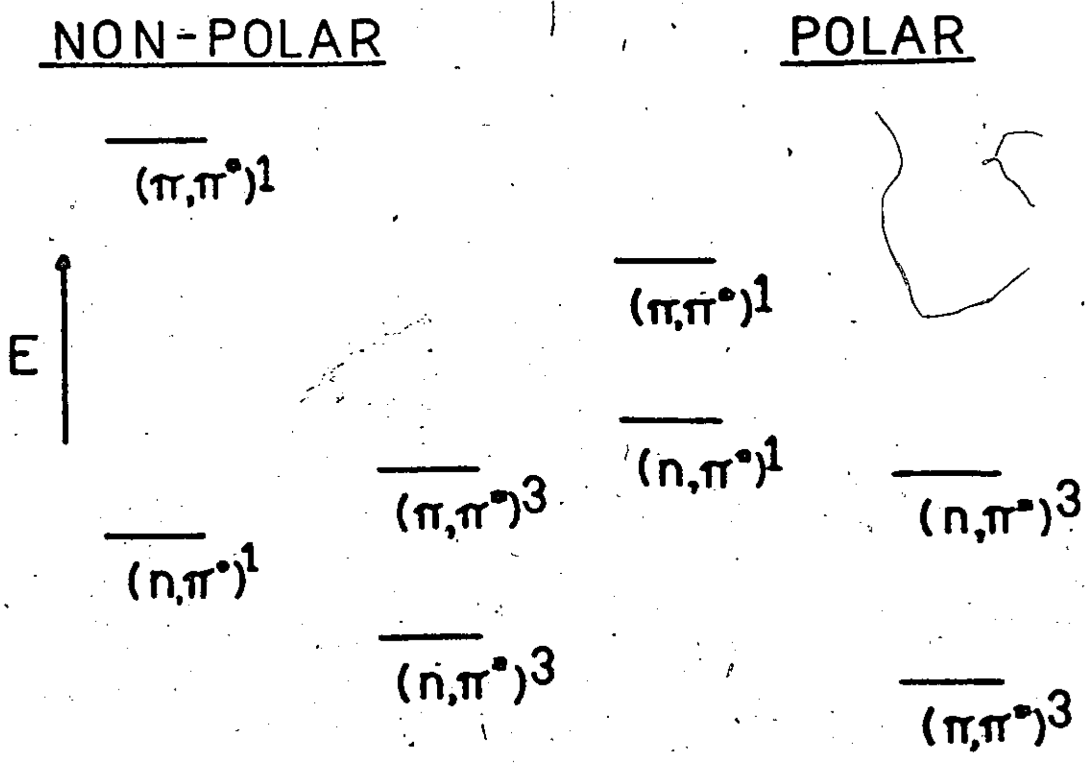
GENERAL PRINCIPLES INVOLVED IN THE PHOTOCHEMISTRY OF UNSATURATED KETONES

(1) The Nature of the Excited State

Absorption of ultraviolet radiation by a ketone results in the promotion of an electron from a bonding or non-bonding orbital to an antibonding orbital. Of the number of possible electronic transitions, only two are of significance in solution. Excitation of an n electron on oxygen to the lowest vacant π^* orbital results in the formation of an (n,π^*) singlet state; the promotion of an electron in the bonding π orbital to the same π^* orbital forms a (π,π^*) singlet. Transitions which involve a change in the spin of the electron are forbidden. Since most organic molecules have singlet ground states, only singlet — singlet transitions are important in absorption under normal irradiation conditions. Triplet states are normally populated by a process called intersystem crossing from the singlet manifold.[1]

Absorption spectra of cyclic unsaturated ketones in non-polar solvents generally display two characteristic bands. The low intensity ($\epsilon < 100$) one found between 300 and 350 nm corresponds to $n \rightarrow \pi^*$ excitation whereas the greater intensity ($\epsilon > 1000$) band at higher energies is the result of $\pi \rightarrow \pi^*$ excitation. Very generally the relative energy levels of excited singlets and triplets are as represented in Figure 1. The energy difference between triplets of opposite configuration is less than that for singlets.[2] Although the $(n,\pi^*)^3$ is shown here as being lower in energy than the $(\pi,\pi^*)^3$, this is not always the case and considerable effort has been expended to determine the relative energies of these states in many systems. The natural lifetime of triplet states with respect to radiative or non-radiative conversion to the ground state is much greater (factor of ca. 10^3) than that of excited singlets.

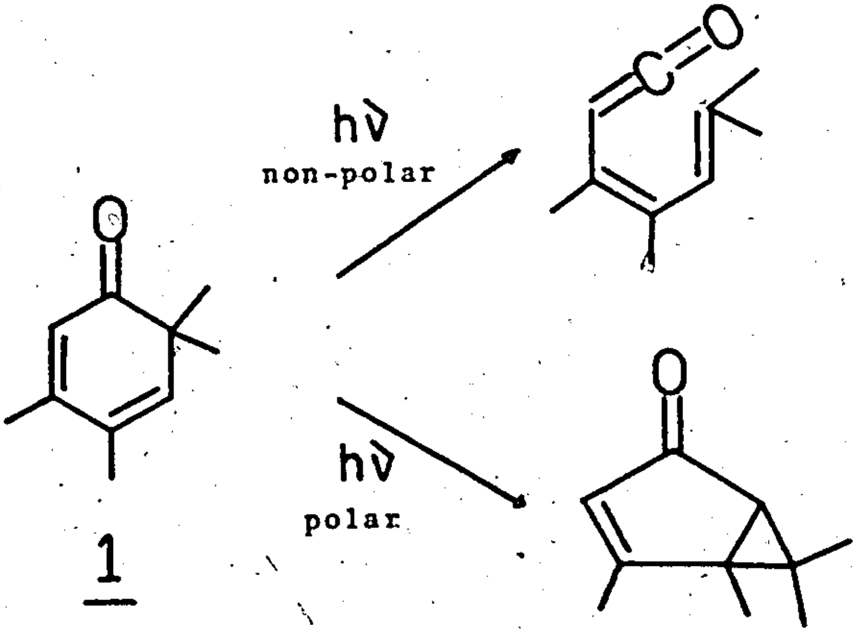
Figure 1. Solvent Effects on Relative Energies of Excited States



The photochemistry of ketones in solution is characterized by the fact that radiationless processes called internal conversion are almost invariably so rapid that the lowest excited singlets and triplets are reached before reaction occurs. For singlet reactions in non-polar solvents it is normally the (n,π^*) state which is responsible. However, in hydrogen bonding, polar solvents such as water or alcohols, the excitation energy of (n,π^*) states is increased (termed blue shift) while that of the (π,π^*) states is decreased (red shift). This change in energy associated with solvent polarity, investigated in some detail by Kosower, is more or less a general phenomenon.^{3} In some cases, the effect is so pronounced that the energy levels will be inverted, as in the case of the triplets in Figure 1. Reactions in these solvents may or may not exclusively involve (n,π^*) states.

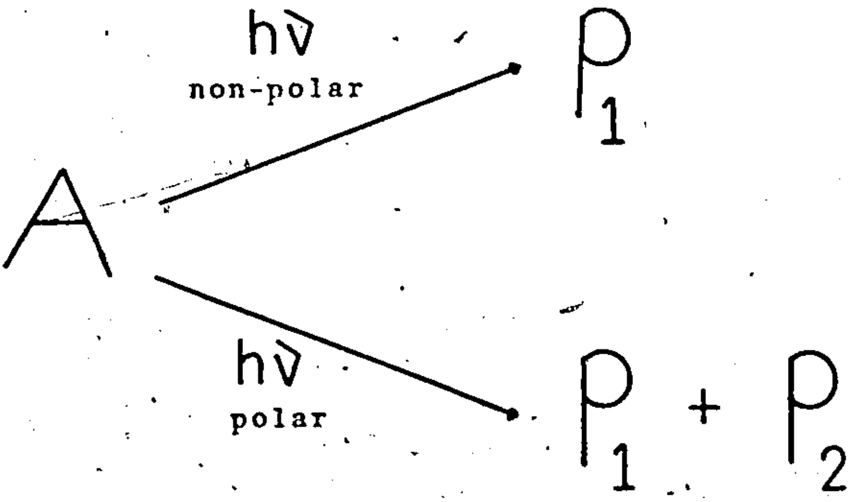
It has been observed that both emission characteristics and reaction pathway can be considerably altered by a change in solvent polarity. Quite dramatically, for example, acetophenone displays a phosphorescence spectrum in non-polar solvents which is characteristic of an (n,π^*) state. In polar solvents this band is replaced by a longer lived, featureless band characteristic of emission from a (π,π^*) state.^{4} Similar effects have been reported for cyclopentenones.^{5} Spectroscopic studies of steriodal cyclohexenones, cyclohexadienones, and related systems indicate that the lowest triplet is (π,π^*) in nature.[6] In a number of these studies, it has been found that the photochemically reactive state is a triplet.

The effect of solvent polarity upon product distribution has been observed in the case of cyclohexa-2,4-dienones[7] and cyclohexenones,[8] for example. Especially striking are the results of a study of the dienone 1.[7a] In hexane, irradiation led to products resulting from a ring-opening reaction to the ketene, whereas in polar solvents direct isomerization to the bicyclic product was observed.



These solvent effects have been explained in terms of changes brought about in the relative energies of the excited states. For example, if ketone A is known to yield product P_1 in non-polar solvents from a singlet, it is presumed that an (n,π^*) state is the reactive species. If the same ketone gives products P_1 and/or P_2 in polar solvents it is suggested that a (π,π^*) state may be the genesis of P_2 and perhaps P_1,[9] Figure 2.

Figure 2. Solvent Effects Upon Product Distribution



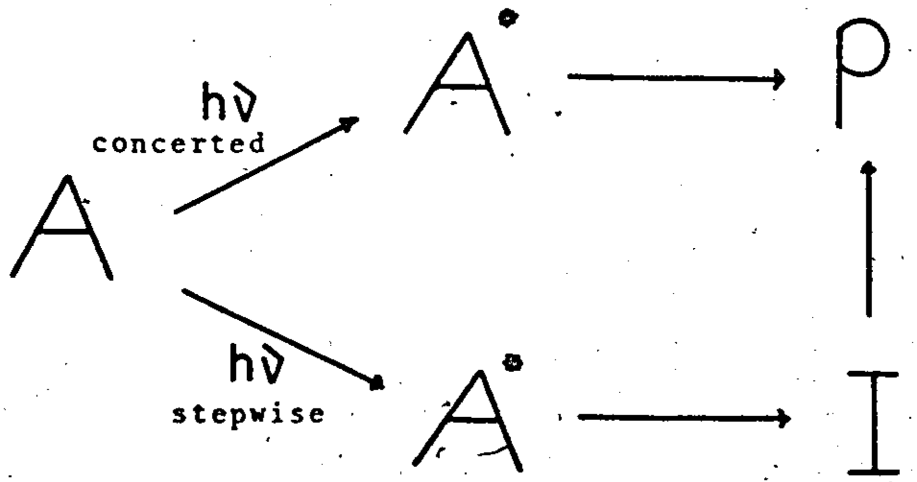
Photochemists have expended considerable effort to elucidate the nature of the excited state in photochemical rearrangement reactions. One probe has been the examination of solvent effects as outlined above. Evidence to corroborate the role of (π,π^*) chemistry is generally lacking and it has been suggested that rearrangements from this state would be of relatively minor significance in ketone photochemistry.[10] Some support for the solvent effect probe has been realized through emission studies. Correlations between spectral and photochemical properties would require that the spectroscopic measurements and the photochemical experiments be carried out under comparable conditions of solvent and temperature. This is not generally the case, however, as most emission studies are conducted upon ketones frozen in a solvent glass at 77°K. Nevertheless, even if these requirements are met, one cannot be completely certain that the radiative state will be the photochemically reactive one.[11] In addition, solvent polarity changes have been observed to affect rates of intersystem crossing, so that alterations in the nature of products may be a result of multiplicity factors.[12]

(2) The Nature of Photochemical Rearrangements of Unsaturated Ketones: General Approaches to Mechanism.

One of the earliest discovered photochemical rearrangements of cyclic unsaturated ketones were the light induced transformations of the sesquiterpene santonin.[13] Since that time it has been found that a large number of related systems undergo a variety of structural rearrangements upon irradiation. The nature of these reactions have attracted interest from both a synthetic and mechanistic point of view. In many cases these isomerizations have provided easy and versatile routes to compounds not conveniently prepared by classical methods.

One of the most fundamentally interesting problems in the field of mechanistic organic photochemistry involves the description of the reaction pathway pursued by an excited state in a photochemical reaction. Solely for didactic reasons, let us consider excitation of ketone A to its excited state A*. Reaction to product could occur in either a concerted or a stepwise fashion through the intermediate I, Figure 3.

Figure 3. Possible Reaction Pathways for Excited States



In a concerted reaction bond rupture takes place simultaneously with formation in a process not involving an intermediate. Concerted reactions are generally stereospecific and are characterized by a low entropy of activation. A number of thermal reactions are known which appear to fulfil both stereochemical and thermochemical kinetic criteria for concertedness.[14] Perhaps the most ubiquitous is the unimolecular cyclobutene-butadiene reaction examined by

Vogel,[15] Criegee,[16] and most recently, Frey.[17] Contrary to general beliefs, concerted reactions do not necessarily follow orbital symmetry considerations, and strong cases have been constructed[18] to show that concerted reactions may be "forbidden" according to the Woodward-Hoffmann rules.[19]

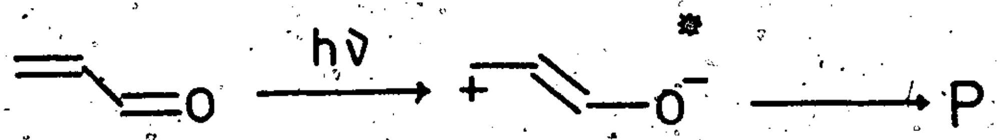
Although a number of photochemical reactions of unsaturated ketones would appear to satisfy the tenets of orbital symmetry conservation,[19] definite evidence is generally lacking to prove that they are concerted. Normally, reactions which are observed to proceed stereochemically in agreement with these rules, or show an indifference to substituent or solvent effects are classified, however correctly, as being concerted. Epiotis, through a series of molecular orbital calculations, has suggested that most photocyclizations are concerted in those cases where strongly electron withdrawing substituents are present in the olefin. He concludes, however, that the Woodward-Hoffman rules apply to only part of the 2+2 and 4+2 reactions studied.[20]

For the most part, photochemical reactions have been described in terms of stepwise pathways. For example, the well-known Norrish "Type I" and "Type II" photoreactions of ketones have been discussed in terms of free radical type intermediates.[1a,b] Intramolecular photoreduction of the carbonyl group is generally considered as a diradical process,[1a] although Srinivasan and coworkers seem to favour a concerted pathway.[21] Formation of oxetanes via 2+2 addition of an olefin and a carbonyl group has also been rationalized through biradical intermediates,[22] however it appears that these could be preceded by the formation of a charge transfer complex.[23]

In many cases, it has been observed that conjugated unsaturated ketones yield rearrangement products upon irradiation which would seem to result from reactions characteristic of electron deficient species, such as hydrogen and alkyl migrations. To explain these apparent carbonium ion processes, two theories have been advanced.

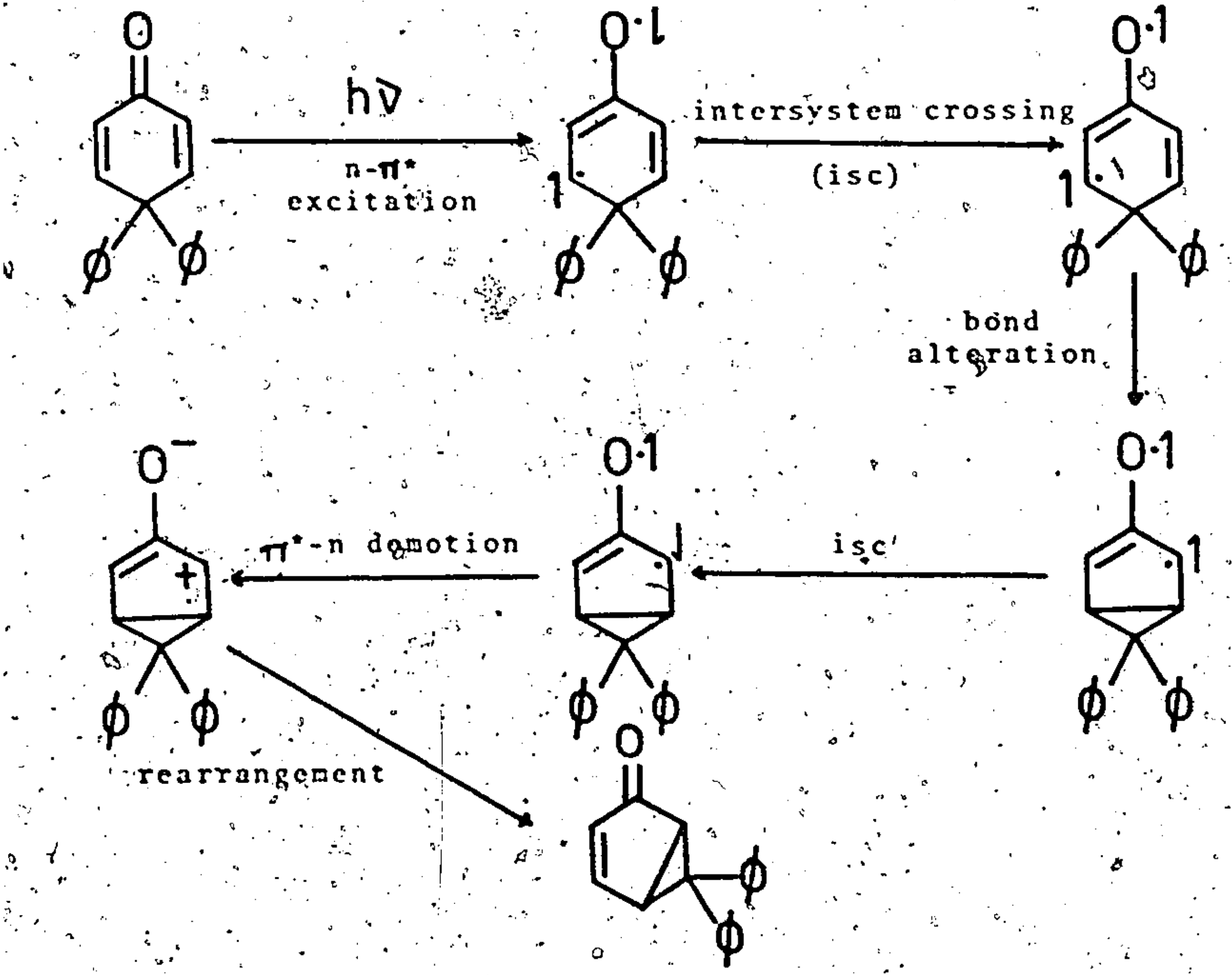
In 1963, Chapman[24] suggested that excitation of a ketone resulted in a dipolar (n,π^*) excited state. This zwitterionic species was assumed to undergo rearrangements typical of carbonium ions. At approximately the same time, Zimmerman[25] advanced a more detailed approach to this phenomenon. It was proposed that the rearrangements of ketones could be accounted for in four steps as outlined below. Without going into the details of Zimmerman's rationale, it may be pointed out that the basic differences

Chapman's Polar State Concept



in these approaches is the chronology of the steps. Whereas Chapman considers a highly polarized (n,π*) excited state, Zimmerman views polarization occurring after demotion of the excited state. Although both can be used to explain photo-rearrangements, the latter scheme does succeed in rationalizing the question of the strongly polarized[26] (n,π*) state advanced by Chapman.

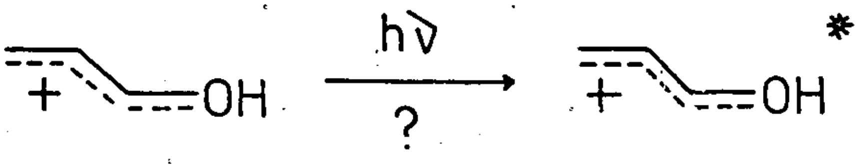
The Zimmerman Approach



Zimmerman has provided excellent evidence for the intermediacy of zwitterions in the photorearrangements of cyclohexa-2,5-dienones and bicyclo[3.1.0] hexenones using techniques such as migratory aptitudes and "photochemistry without light" experiments.[27] A study of the migratory behaviour of substituents in cyclohexenone photoisomerizations suggest that ground state zwitterions are not involved and that rearrangement occurs in a diradical excited state.[28] Despite the comprehensive nature of his work, he has not escaped criticism or opposition.[29]

There is no general method which permits an unambiguous assessment of the nature of the excited state and intermediates in photochemical rearrangements of unsaturated ketones. Those methods developed by Zimmerman are extremely powerful for specific systems undergoing a specific rearrangement. The solvent effect approach has been used most often but is by no means without difficulties and ambiguities.

One approach to overcoming this problem would be to "force" the ketone to undergo rearrangements of an electron deficient nature from a (π,π^*) state and compare the products obtained with those from direct irradiation. An analogy to this idea is the well-known sensitization technique which is employed to determine the multiplicity of an excited state.[30] By "sensitizing", the ketone is forced to react from its lowest triplet state and the products obtained from this route are compared to those in unsensitized runs. With regards to the present case, it appeared interesting to determine whether one could induce (π,π*) type rearrangements by exciting the corresponding protonated ketone.

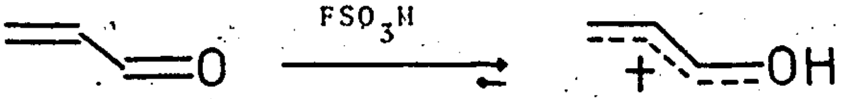


2

To get an idea of the potential of this technique it is necessary to examine the formation of the hydroxy cations and their fate upon excitation.

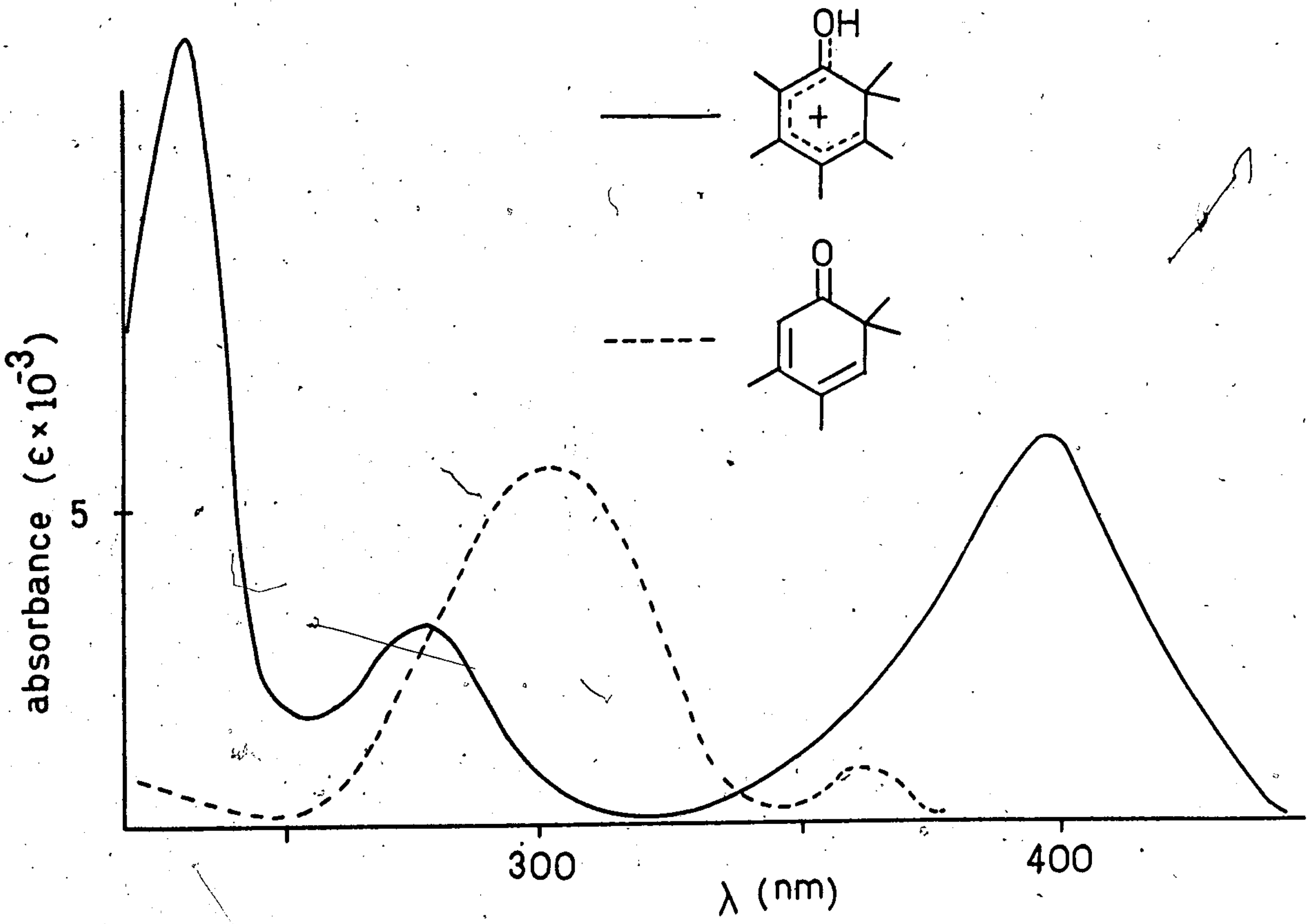
Unsaturated ketones dissolve in super acids such as fluorosulphuric, FSO_3H, to form the corresponding protonated ketone, 2, Figure 4.[31] The difference in Ho of the protonated base and FSO_3H, ca. 10^8, will effectively ensure that the equilibrium lies far to the right.[32] By using light of suitable wavelength, irradiation of these solutions can result in excitation of only the cation.

Figure 4. Protonation of Unsaturated Ketones



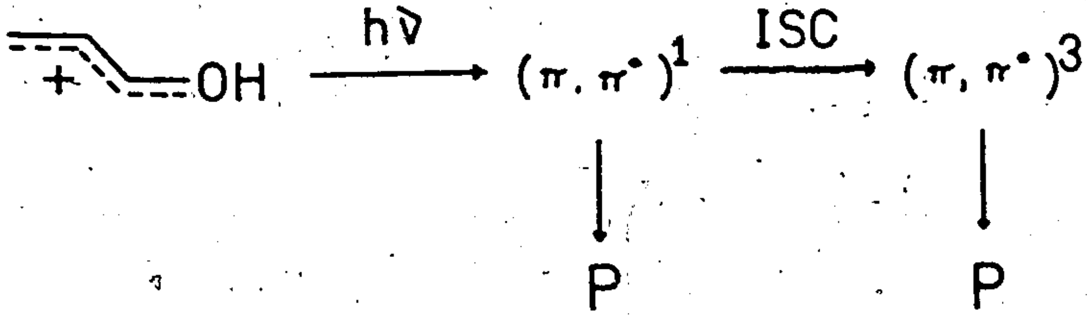
2

Figure 5. Uv Spectra of a Dienone and a Protonated Dienone



It has been pointed out earlier that both n $-\pi^*$ and $\pi-\pi^*$ transitions are possible upon excitation of ketones in solution. In polar, hydrogen bonding or acidic solvents the non-bonding electrons on oxygen become coordinated to the solvent and hence require more energy to excite.[3] In strong acids such as FSO_3H, these electrons enter into a bond with a proton.[31] The energy necessary to cause a transition of the n electrons exceeds that required for the π electrons. No (n,π^*) band is observed in the ultraviolet absorption spectrum of hydroxy cations at low energies; instead one observes a relatively high intensity, low energy band due to $\pi-\pi^*$ transitions[33,34], Figure 5. The excited state which forms as a result will be (π,π^*) in nature. Spin conservation laws should ensure that the initially reached state be a singlet. Intersystem crossing from this state to the triplet manifold could give rise to the (π,π^*) triplet of the hydroxy cation. Subsequent reaction from either (π,π^*) state would be expected to be characteristic of an electron deficient species, Figure 6.

Figure 6. Excited States of a Protonated Unsaturated Ketone



If the photoisomerization of the protonated ketone and the corresponding ketone yield identical products, a parallel may exist in the nature of the excited states involved and the mechanism of the reactions. If this parallel is shown, then one can readily discern how this approach would be of general applicability to assess the role of (π,π^*) excited states and ionic intermediates in the photochemistry of the neutral ketone.

Is there any evidence to indicate that such a comparison may exist?

(3) The Photochemistry of Protonated Ketones

Photochemical reactions of stable carbonium ions have only recently received any serious attention.[35] The interest in this field has no doubt been abetted by the development of techniques capable of observing carbonium ions under long-lived conditions. Work pioneered by Meerwein[36] and furthered by Olah[37] and Gillespie[38] has made accessible a series of extremely stable carbonium ion systems.

The first example of the photoisomerizations of protonated ketones was reported by Childs.[34] This work was continued by Parrington[35c] and is important in that it appears to define the nature of the photoreactions of some protonated cyclohexadienones in FSO_3H. Without comprehensively reviewing this work, it is possible to draw attention to the close parallel between these reactions and those of analogous ketones.

It was observed that irradiation of the protonated hexamethyl cyclohexa-2,4-dienone, <u>3H</u>, yielded the bicyclic isomer, <u>4H</u>, which underwent further photoreaction under these conditions.[39] Of a number of *a priori* mechanisms, it was concluded from a study of substituent effects that the rearrangement proceeded via initial closure to the intermediate, which then thermally isomerized to the product, Figure 7. Earlier, Hart had suggested that the corresponding ketone reacted from the (π,π^*) singlet in trifluoroethanol via the zwitterion intermediate to give the hexamethyl bicyclo[3.1.0] hexenone, Figure 7.[7b] The comparison is striking considering the disparate nature of the reactants.

Interestingly, the photoisomerization of protonated 4,4-dimethylcyclohexa-2,5-dienone, <u>5H</u>, to protonated 6,6-dimethyl-bicyclo[3.1.0] hexenone reported by Parrington and Childs[39] parallels that of the neutral ketone, <u>5</u>, studied by Swenton in 1968.[29b] Swenton concluded that ionic intermediates were not involved in the gas phase photorearrangement to the bicyclic ketone. This conclusion contradicted those proposals made by Zimmerman[10] and would appear to be in direct contrast to the apparent nature of the reaction in FSO_3H. His deduction was made on the assumption that, in the absence of solvation, ionic intermediates would be of too high energy in the gas phase. The validity of this assumption must be questioned in view of the results obtained

Figure 7. Photoisomerization of a Dienone and a Protonated Dienone I

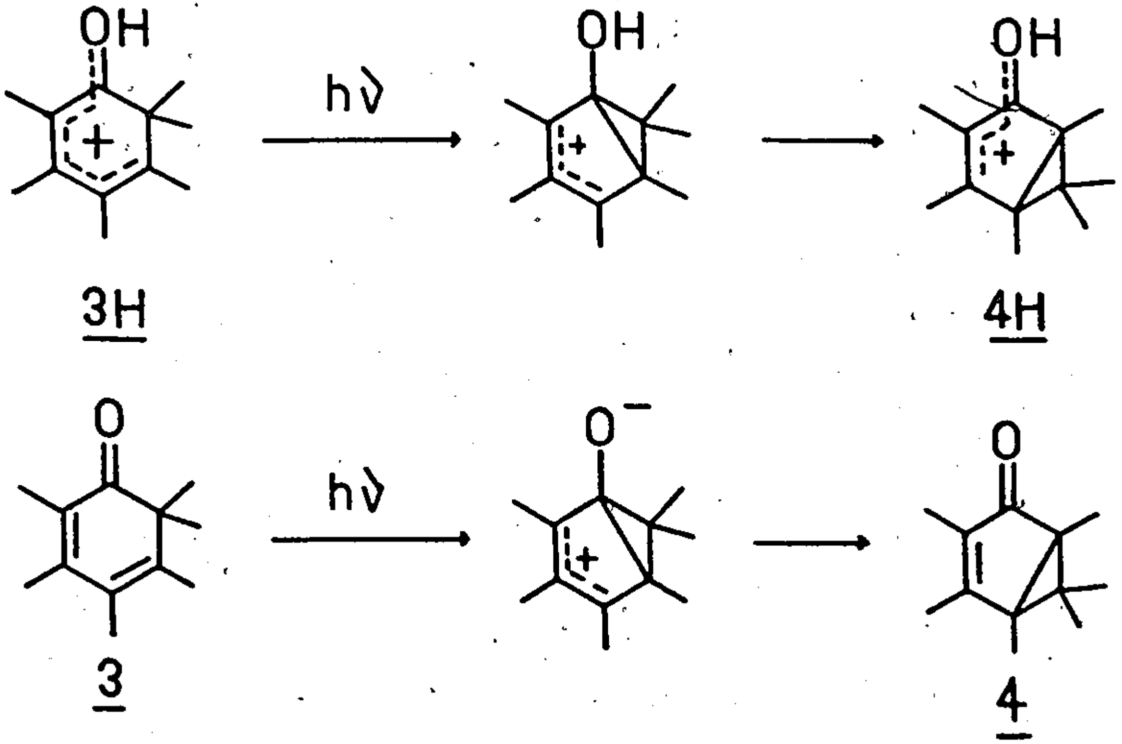
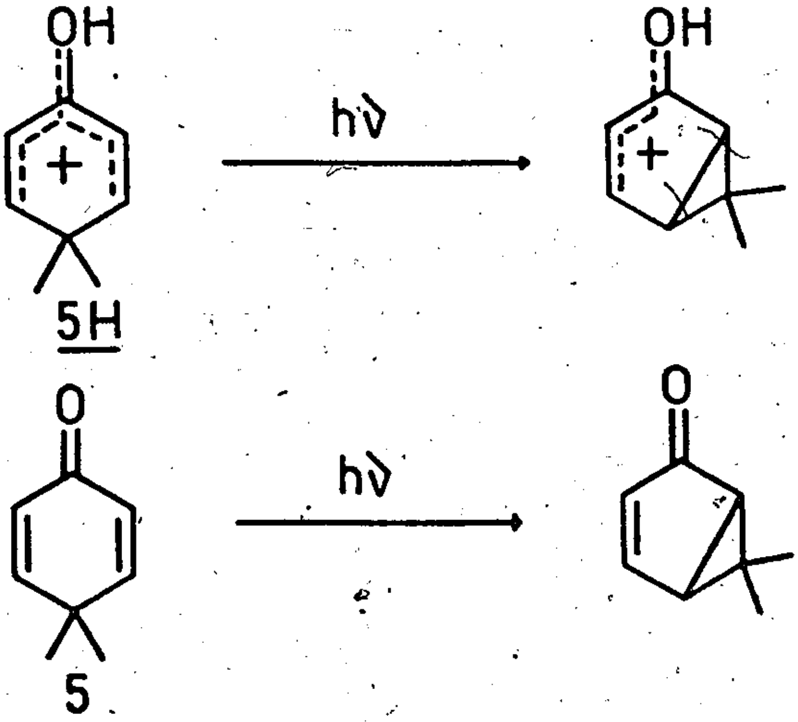


Figure 8. Photoisomerization of a Dienone and a Protonated Dienone II

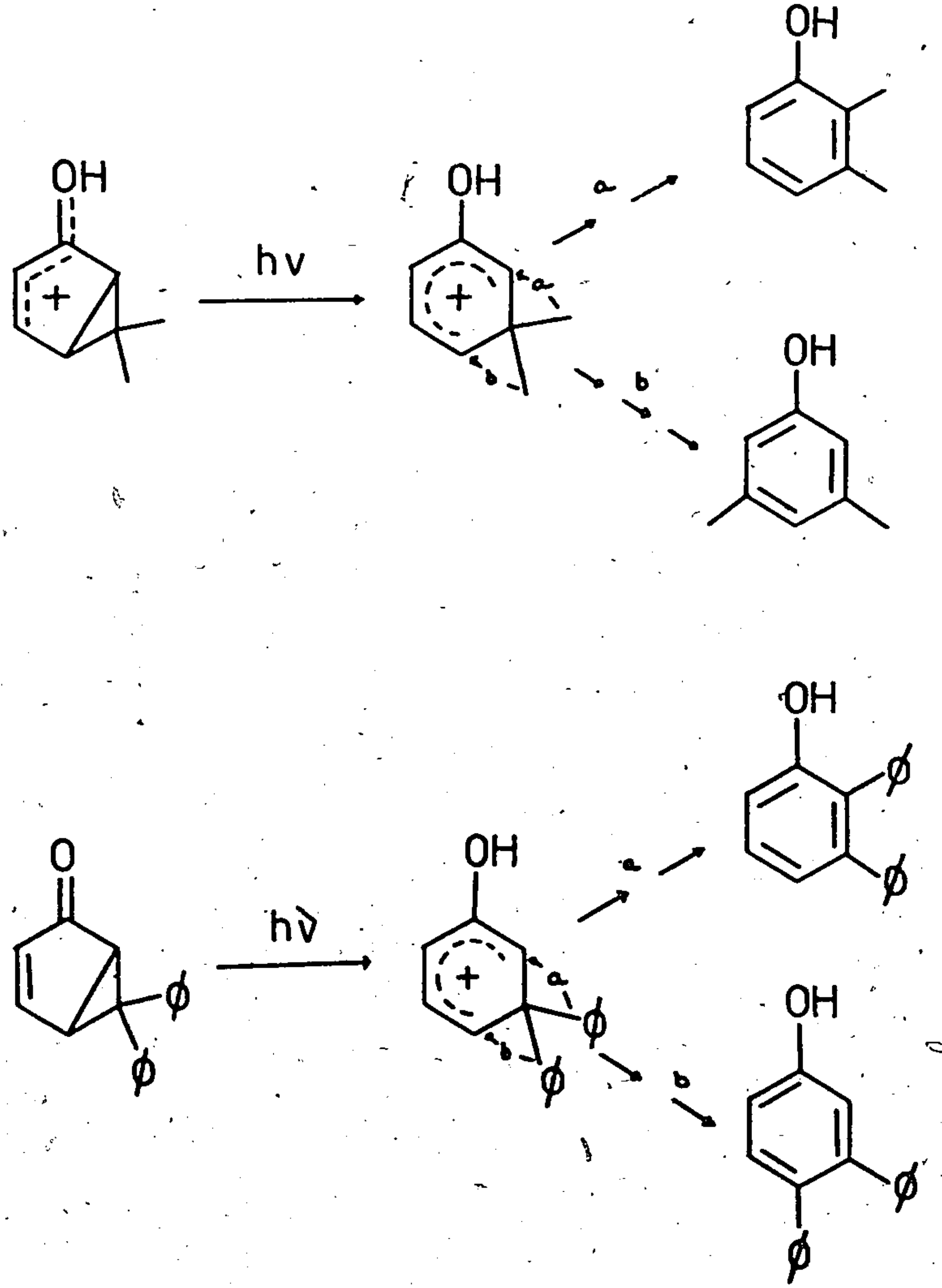


by Hoffmann in which he calculated, using extended Huckel calculations, that cyclopropanone is expected to be less stable than the oxyallyl zwitterion.[40]

In this study, Parrington reported two further products not observed by Swenton. It was suggested that the isomeric phenols shown in Figure 9 arose as a result of 1,2-methyl shifts in the intermediate generated photochemically from protonated 6,6-dimethylbicyclo[3.1.0] hex-3-en-2-one.[35c] Somewhat related to this, Zimmerman had observed that irradiation of 6,6-diphenylbicyclo[3.1.0] hex-3-en-2-one in buffered acidic dioxane yielded two isomeric phenols whose ratio was dependent upon the apparent pH of the solvent.[41] Zimmerman concluded that these phenols were formed via a 1,2-phenyl migration in the protonated zwitterion (Figure 9).

There appeared to exist a relationship between the photoreactions of some unsaturated ketones and their protonated analogues, although in only one case were (π,π^*) states implicated in the photochemical reaction of the ketone. If a study of the photoisomerization of a protonated ketone is to be meaningfully applied to the question of (π,π^*) chemistry and ionic intermediates, the relationship, such as those assembled above, must be examined more systematically and in greater detail. The remainder of this thesis describes the results and implications of such an investigation into these questions pertaining to the photochemistry of the cyclohepta-2,4-dienone, eucarvone 6.

Figure 9. Photoisomerization of an Enone and a Protonated Enone

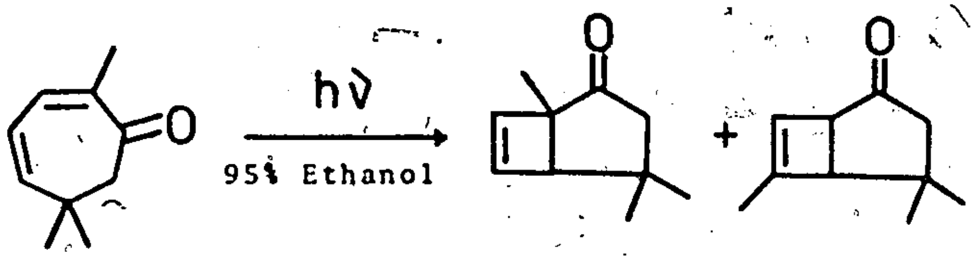


PART 2. THE PHOTOCHEMISTRY OF EUCARVONE AND PROTONATED EUCARVONE

RESULTS AND DISCUSSION

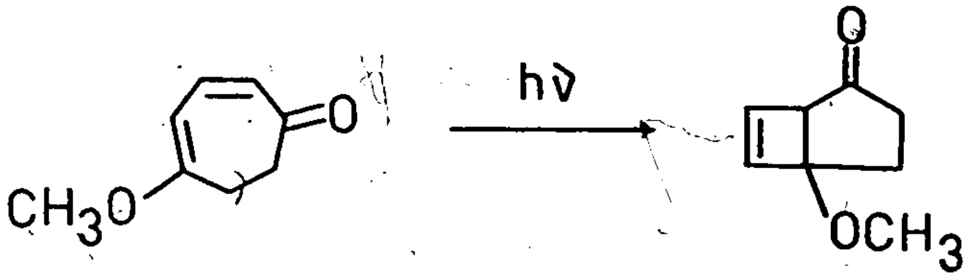
INTRODUCTION

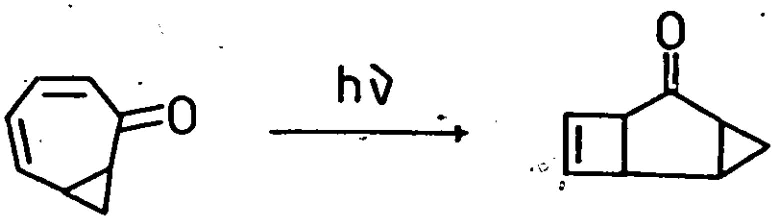
In 1960 Büchi and Burgess reported that irradiation of eucarvone in 95% ethanol resulted in the formation of two isomeric ketones, 7 and 8.[42] The former was shown to arise directly from 6 whereas 8 resulted from further reaction of 7. Separate irradiation of either 7 or 8 yielded the same 4:1 mixture. In refluxing benzene containing a trace of para-toluenesulphonic acid, 7 rearranged thermally to 8.



6 7 8

The authors claimed that this acid-catalyzed reaction provided the evidence for a cis ring juncture in 7. A number of other cyclohepta-2,4-dienones are known to photochemically react in an analogous fashion although details of these reactions were not reported.[43]

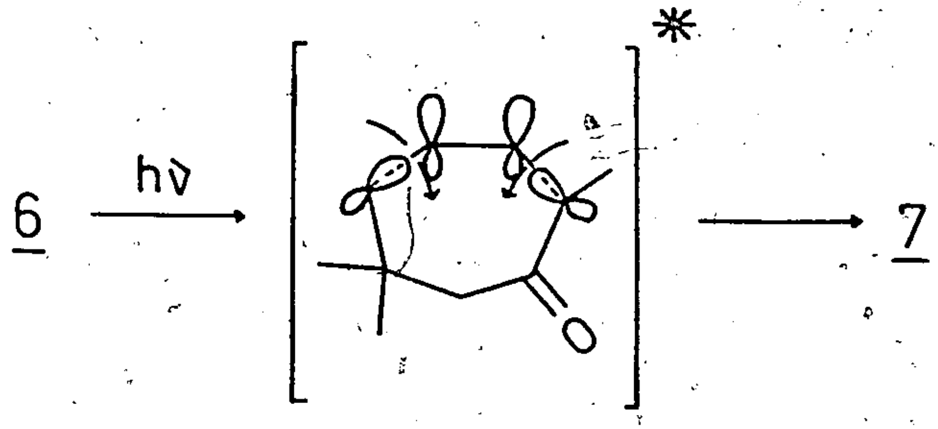




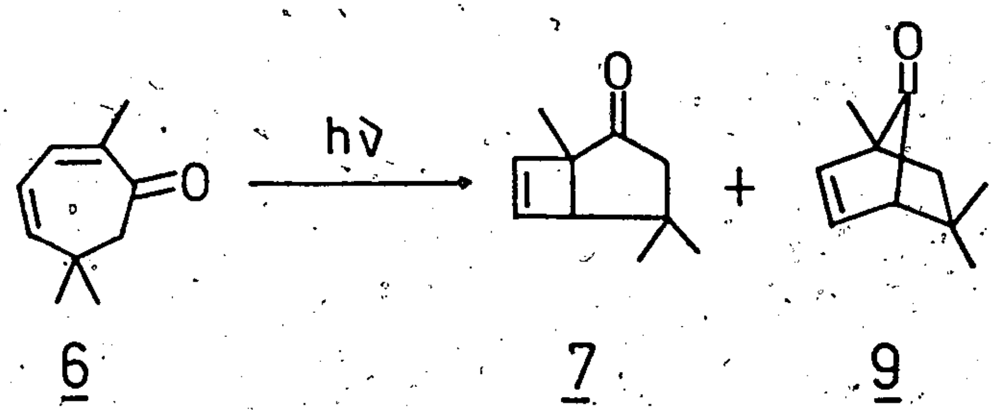
Schuster furthered the investigation of the 6 to 7 reaction and found that it was a somewhat inefficient process in benzene ($\phi = 0.0025$) but that the rate of formation of 7 increased with solvent polarity.[44] Quenching and sensitization studies suggested that this reaction occurred from both a singlet state (60%) and a triplet state (40%) of 6. The formation of 7 from eucarvone can be reasonably thought of in terms of a symmetry allowed $\pi 2+\pi 2$ closure which photochemically would occur in a disrotatory fashion.[19]

Studies by others demonstrated the complexity of eucarvone photochemistry. Hurst and Whitham reported that irradiation of 6 in 40% aqueous acetic acid yielded two

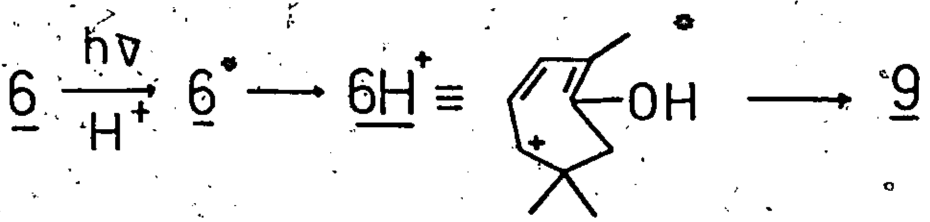
The Formation of 7



products which were separated on aluminia.[45] Formed in approximately equal amounts, they were identified as 7 and the norbornenone 9. These authors speculated that since 9 was obtained only in acidic solvents, its formation could occur via a protonated (π,π*) excited state of 6. Considering the chemistry of other cyclohepta-2,4-dienones, this reaction would appear unique to 6. Perhaps solvent acidity and/or substituents were a necessary prerequisite, although no information was available.



The Formation of 9



The question of a protonated (π,π*) state is interesting and further comment is appropriate. At the time of Hurst's and Whitham's work it had been established that the basicities of the excited states of aromatic carbonyl compounds were orders of magnitude greater than that of the corresponding ground states.[46] As an example, the pKa of acetophenone is increased by a factor of 10^5 in its excited state.[46b] Other ketones and related carbonyl compounds showed similar enhancements.[47] It had been demonstrated that protonation and deprotonation could be sufficiently rapid processes that they could occur during the average lifetime of a singlet (10^{-9} sec) or triplet (10^{-6} sec) state.[47a]

Accordingly, it is a reasonable thesis that excited states could undergo acid-base reactions not normally important for their ground state precursors. Despite the number of photochemical reactions which appear to be catalyzed by acid,[48,49] the area has not been treated with the same degree of rigour which other fields of photochemistry have experienced. Two reasonable approaches have been formulated to explain a frequently observed dependence of photochemical transformations of enones and dienones upon solvent acidity, Figure 10.

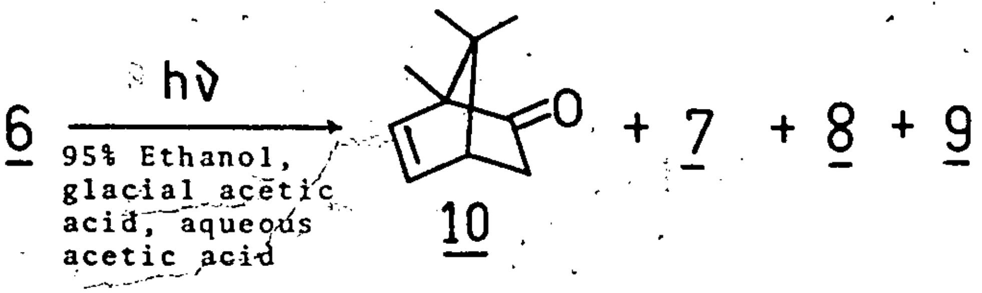
Protonation of an excited singlet or triplet state has been suggested, as in the eucarvone example, to rationalize the formation of additional products obtained only in acidic solvents. Presumably, proton transfer to an excited state could affect its lifetime, energy, or electron distribution, which in turn could alter its reaction course. The alternative viewpoint, which enjoys more support in the literature, is that protonation would occur upon the zwitterionic intermediate, so often proposed in ketone photoisomerizations. It would seem that the subsequent rearrangements of these dipolar species can be modified via protonation of the electron rich oxygen.[48b] With regard to

Figure 10. Excited State Protonation Verses Zwitterion Protonation

$$A \xrightarrow{h\nu} A^{*} \xrightarrow{H^{+}} \overset{*}{A}H^{+} \qquad A \xrightarrow{h\nu} A^{*} \rightarrow \rightarrow \underset{+}{A^{-}} \xrightarrow{H^{+}} AH^{+}$$

the excited state protonation route, it is interesting to question the relationship between this proposal for eucarvone and the potential rearrangement of the corresponding protonated ketone upon excitation.

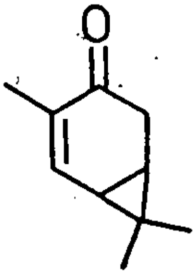
Subsequent to the work by Hurst and Whitham, another photoproduct was obtained from eucarvone, in a variety of solvents, and identified as dehydrocamphor, 10[50]. As shown below, the product ratios were observed to vary with the solvent.



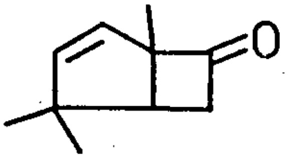
(10-25%) (10-20%) (45-79%) (5-12%) (1-20%)

The complexity of eucarvone photochemistry was recognized by Schuster. He suggested either that one intermediate (ionic or radical?) partitioned to 7, 8, 9, and 10, or that several competing processes occurred concurrently, the rates of which depended upon the nature of the solvent. Several years later, the situation was somewhat delineated by Takino and Hart.[51]

It was reported by these workers that the absorption maximum of 6 was red-shifted from 303 nm in ethanol to 310 nm in trifluoroethanol and to 318 nm in silica-gel cyclohexane with no appreciable change in intensity. When solutions of 6 adsorbed on silica-gel in cyclohexane were irradiated, a complex mixture of products was obtained. In addition to those already reported, they discovered two previously undetected ketones which were identified as 11 and 12.



11

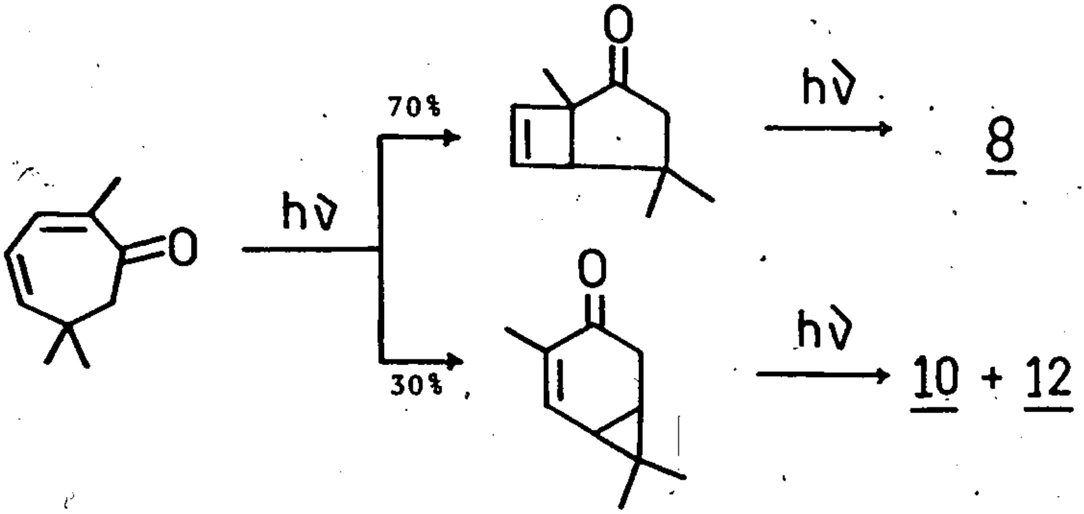


12

Interestingly, under comparable irradiation times in cyclohexane without silica gel, the reaction of 6 was slower and produced only 7! In independent runs it was established that this new photoproduct 11 photoisomerized in silica-gel cyclohexane to 10 and 12. Hart concluded from these experiments that 6 rearranged in highly polar solvents via two routes which yielded only 7 and 11 as primary products. The others observed were considered to arise from a subsequent photoreaction of 7 or 11, Figure 11.

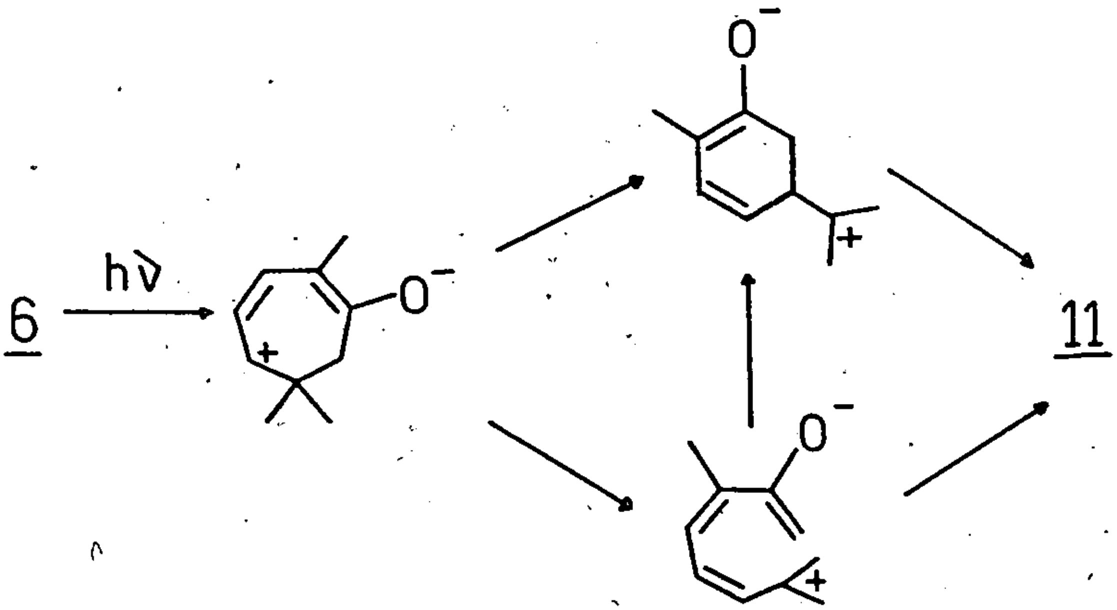
It was at this stage in the investigation of eucarvone that the present study of protonated eucarvone photochemistry was commenced. Several months later Hart published a full paper in which he elaborated on his earlier results.[52] Since it was found that neither piperylene nor cyclohexa-1,3-diene appreciably quenched the formation of 7 and 11, it was

Figure 11. Photoisomerization of Eucarvone in Polar Media



suggested that they may arise from the same excited singlet of 6 or from two states close in energy. No evidence was available to allow a distinction between these alternatives. In addition, since 11 was not formed in acidic solvents it was proposed that silica-gel cyclohexane or trifluoroethanol did not act as proton donors and effect isomerization through the (π,π^*) state of the protonated dienone. Instead, Hart advanced that these polar solvents inverted the relative energies of the (n,π^*) and (π,π^*) excited states.

Mechanistically the formation of 11 from 6 was viewed[52] as a stepwise process involving, perhaps, several zwitterionic intermediates. A concerted $\sigma 2a+\pi 2a$ pathway was disfavoured in light of the solvent effect.[52]



However, it was not possible to make a choice among the three pathways shown above.

The objective of the work described in this thesis was to examine the photoisomerization of protonated eucarvone with the intention of assessing the role of (π,π^*) excited states and possible ionic intermediates implicated in the complex photochemistry of the neutral ketone. Since protonated eucarvone perforce would react from a (π,π^*) state, such a study could definitely elucidate the nature of the excited states leading to 7, 11, and 9.

To discuss properly the implications of this investigation, it was found necessary to re-examine several aspects of neutral eucarvone photochemistry and to establish the nature of the intermediates involved in the (π,π^*) route of both ketone and protonated ketone. Subsequent sections of this thesis deal with these studies.

(2) PHOTOISOMERIZATION OF PROTONATED EUCARVONE

(i) The Protonation of Eucarvone

Addition of 6 to FSO_3H at -78° resulted in a deep yellow solution whose spectroscopic properties were indicative of the formation of the corresponding protonated ketone 6H.

A comparison of the pmr spectra in CCl_4 and FSO_3H at +37° revealed that the protons in 6H were shifted to lower field, Table 1. This deshielding effect which is most pronounced for the vinyl hydrogens indicates substantial positive charge upon the dienyl moiety and is fully consistent with the delocalized hydroxy dienylic nature shown in Figure 12.

TABLE 1. Pmr Spectra of Eucarvone and Protonated Eucarvone[a]

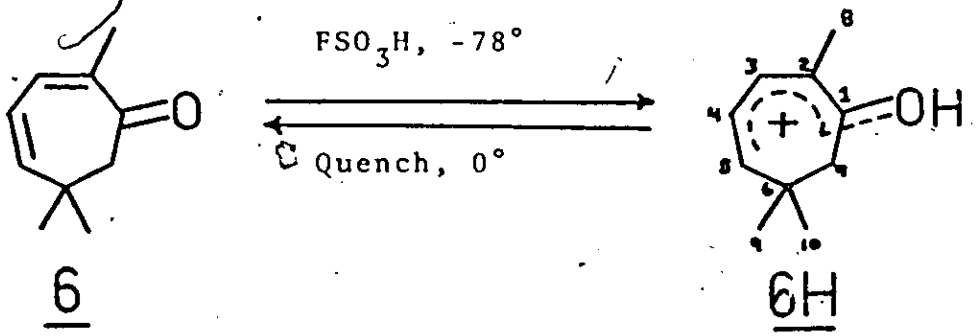
Compd	H_3	H_4	H_5	H_7	C_2-Methyl	C_6-Methyls	Coupling Constant[b]
6	3.64	4.32	4.10	7.47	8.16	8.97	$J_{3,4}$=8.0, $J_{4,5}$=11.3
6H	2.14	3.50	3.13	6.67	7.78	8.72	$J_{3,4}$=8.2, $J_{4,5}$=11.5

---

[a] HA100 spectra using internal TMS(τ10.00) for 6 and CH_2Cl_2(τ4.70) for 6H as standard references.

[b] ±0.3 Hz.

Figure 12. The Protonation of Eucarvone



The proton bonded to C_3 experiences the greatest deshielding suggesting that this carbon atom bears the largest fraction of positive charge. We can get an idea of the charge density at C_3 through a consideration of the ^{13}C nmr spectrum, Table 2, of 6H.[53] The relationship between charge density and carbon shift has been evaluated at *ca*. 160 ppm per unit charge.[54] Since C_3 is deshielded by 32.6 ppm[53] it can be estimated that 0.20 positive charge resides on this atom. C_5 experiences a somewhat smaller effect (19.5 ppm), corresponding to 0.12. The remainder of the charge must be on oxygen as the ^{13}C shifts of C_1, C_2, and C_4 remain essentially unchanged upon protonation.

The nature of the charge delocalization is in complete agreement with that of similar protonated dienones which have been studied.[31,55] The major resonance contributors to 6H are shown below. It has been suggested the bias in the charge distribution might derive from a preference of the counter ion, FSO_3^-, for the C_3 position.[53]

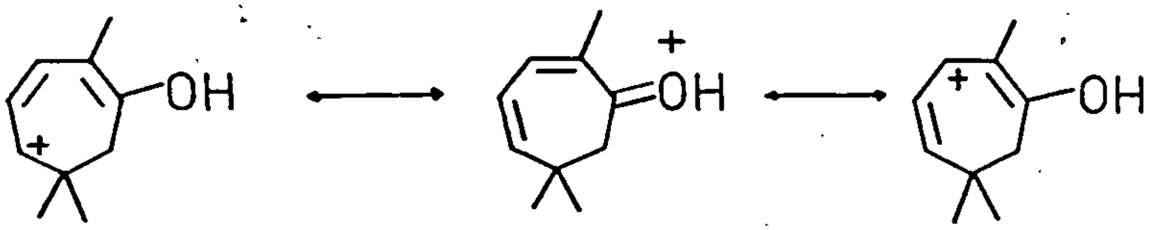
TABLE 2. ^{13}C Protonation Shifts for Eucarvone

Position	^{13}C Shifts (ppm)[a,b]
1	7.1
2	- 4.2
3	32.6
4	3.9
5	19.5
6	1.5
7	- 4.6
8	- 2.2
9,10	- 3.3

[a] ± 0.1 ppm

[b] Results taken from reference 53, negative sign indicates upfield shift.

Resonance Contributors to the Structure of 6H



One important aspect of the pmr spectra of 6 and 6H is the similarity in olefinic pattern and vinylic coupling constants. This emphasizes the fact that protonation occurs upon oxygen and not upon the diene fragment of the molecule. The pKa of protonated eucarvone has been determined as -4.9 in the H_0 scale.[56] Considering the acidity of FSO_3H, Ho = -15,[57] it can be readily seen that only one molecule in ca. 10^{10} is unprotonated in this acid.

A comparison of the ultraviolet absorption spectra of 6 and 6H provides further support for the ionic nature of protonated eucarvone, Table 3. A shift of this magnitude for the $\pi-\pi^*$ band is consonant with O-protonation.[31a,58]

Neutralization of the acid solution containing 6H with aqueous sodium bicarbonate at 0° recovered 6 unchanged in quantitative yield. In FSO_3H, 6H was stable at +23° for at least 24 hours but at temperatures exceeding +60° rearrangement and decomposition took place.

TABLE 3. Ultraviolet Spectra of 6 and 6H[a]

Compd	uv max (nm)	logϵ
6 [b]	303	3.93
6H [c]	400	3.63

[a] at 23°, [b] in methanol [c] in 96% H_2SO_4

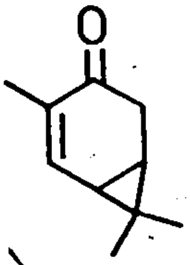
(ii) The Irradiation of Protonated Eucarvone

Solutions of 6H in FSO_3H contained in clear-walled nmr tubes were irradiated at temperatures below -75° with light of λ>370 nm. After two hours all 6H had reacted and the pmr spectrum of the resultant acid solution suggested a mixture of products. Low temperature neutralization yielded an oil which glpc analysis indicated that it contained three products in the ratio of 1:4:15. All photoproducts were collected by preparative glpc as oils.

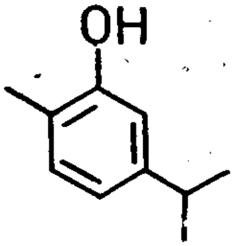
The major product was shown to be 11 by comparing its spectral properties, Table 4, $\nu_{C=O}$ = 1665 cm^{-1}, to those reported by Hart[51] and Zabza[59] for 11. This product was identical in all respects to authentic material obtained by the procedure of Hart.[51,52]

The 20% product had a molecular ion in the mass spectrum at m/e = 150 and a strong absorption in the ir at

3600 cm^{-1} but no carbonyl band. The pmr spectrum, Table 4, suggested this product was 2-methyl-5-isopropylphenol, 13.



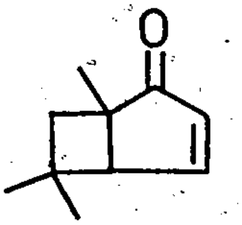
11 8



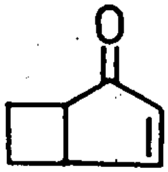
13

Comparison of these spectral properties with those of authentic carvacrol, 13, confirmed the assignment. Both had identical ir and pmr spectra and identical glpc retention times.

The third photoproduct which was formed consistently in very minor amounts, *ca*. 5%, was shown by combustion and spectral data to be the bicyclo[3.2.0]heptenone 14. Compound 14 was isomeric with 6 ($^{m}/e$ = 150, % C = 79.98, % H = 9.44) and displayed an ir spectrum, $\nu_{c=0}$ = 1715 cm^{-1}, and uv spectrum, $\lambda_{max}^{CH_3OH}$ = 236 nm log ϵ = 3.75 which suggested a cyclopentenone.[60,61] The vinyl region of the pmr spectrum, Table 4, consisted of two, one proton multiplets almost identical in pattern and chemical shift to that reported by Paquette[60] for the parent bicyclo[3.2.0]hept-3-en-2-one, 15. The high region was equally informative. Three sharp singlets each corresponding to three hydrogens were assigned to the three methyl groups. The one proton multiplet,



14



15

$J_{4,5}$ = 3.0 Hz, was assigned to the C_5 bridgehead position, and the two proton broad singlet at τ 8.30 to the C_7 methylene group.

Each of 11, 13, and 14 could be reprotonated in FSO_3H at -78° to form the corresponding hydroxy cations 11H, 13H, and 14H as shown in Figure 13. The pmr spectrum of 11H is consistent with O-protonation and a delocalized positive charge. Protonation of 13 occurs upon the para position of the ring to give the hydroxy dienylic cation. Similar results were obtained for 2,5-dimethylphenol.[35c] The extremely deshielded vinyls of 14H are characteristic of protonated cyclopentenones reported by Olah[31c] and Childs.[62] At -30° these cations were stable to rearrangement and decomposition for at least one hour.

The photoisomerization of protonated eucarvone could be summarized as in Figure 13. By using tetramethylammonium

Figure 13. Irradiation of Protonated Eucarvone

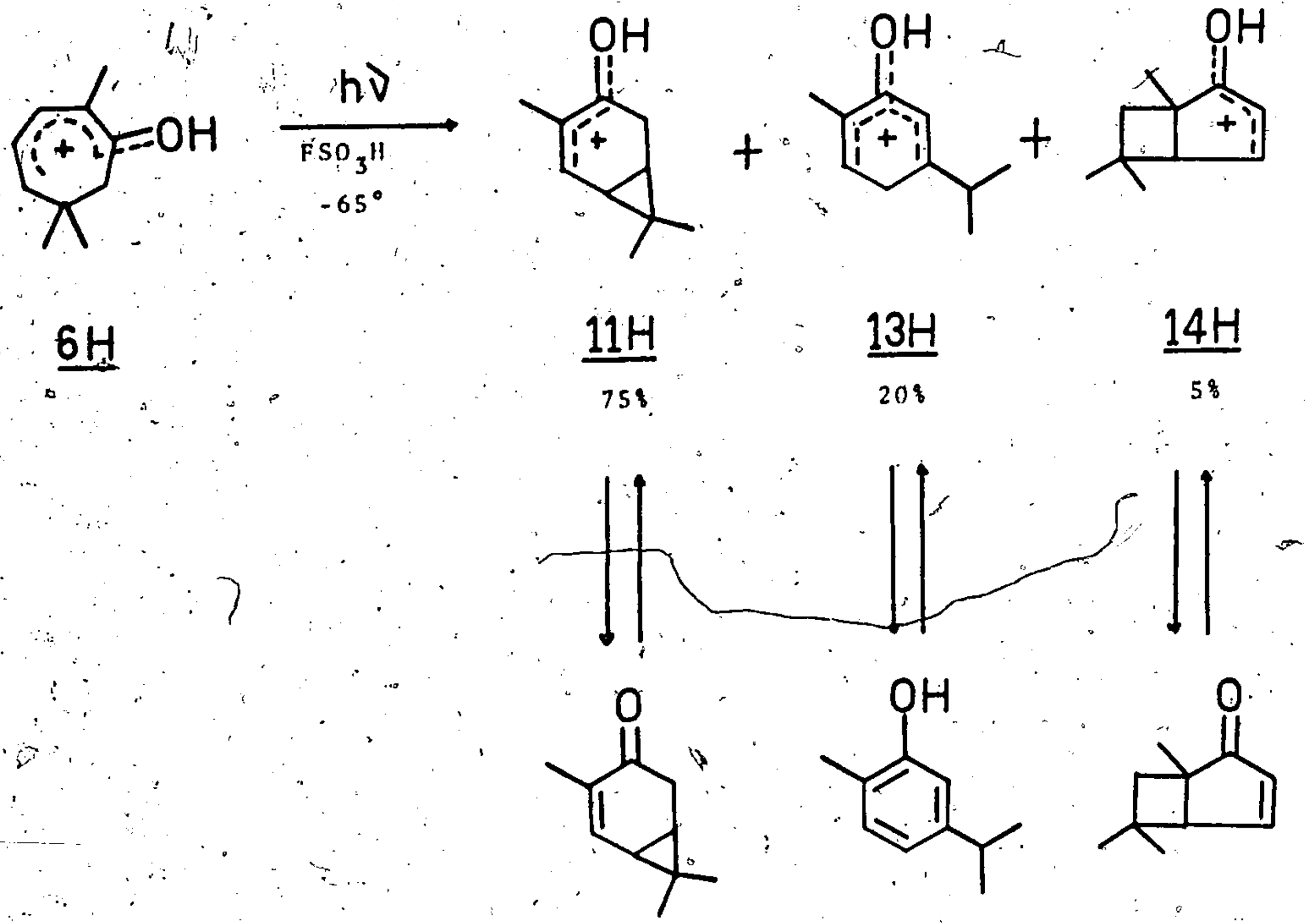


TABLE 4. Pmr Spectra of the Products from the Irradiation of Protonated Eucarvone[a]

Compd	H_1	H_2	H_3	H_4	H_5	H_6	H_7	Methyls	Coupling Constants[b]
11	8.8	3.35	—	—	7.58	8.8	—	8.34,8.82,9.22	
11H[c]	8.7	1.90	—	—	7.15	7.7	—	7.92,8.45,9.02	
13	4.55[d]	—	3.04	3.36	—	3.48	7.24[e]	7.82,8.82 (J=7)	$J_{3,4}$ = 7.5, $J_{4,6}$ = 1.9, $J_{3,6} \approx 0$
13H	—	—	1.88	5.90	—	2.86	6.92[e]	7.78,8.66 (J=7)	
14	—	—	3.85	2.55	7.38	—	8.30	8.67,8.80,9.12	$J_{3,4}$ = 5.5, $J_{4,5}$ = 3.0
14H	—	—	2.80	0.92	6.50	—	7.58 8.14	8.56,8.58,9.09	$J_{3,4}$ = 5.5, $J_{4,5}$ = 2.5, $J_{7,7'}$ = 13.0

[a] At 100MHz, ketones in CCl_4 (TMS internal reference) at + 37°, cations in FSO_3H (CH_2Cl_2) at -30°, unless stated otherwise.

[b] ± 0.3 Hz

[c] at 60 MHz

[d] O-H proton

[e] i-propyl proton.

chloride as internal standard in the acid solutions it was observed that only ca. 5% material loss occurred during irradiation. Careful neutralization could recover the products in high yield (90%).

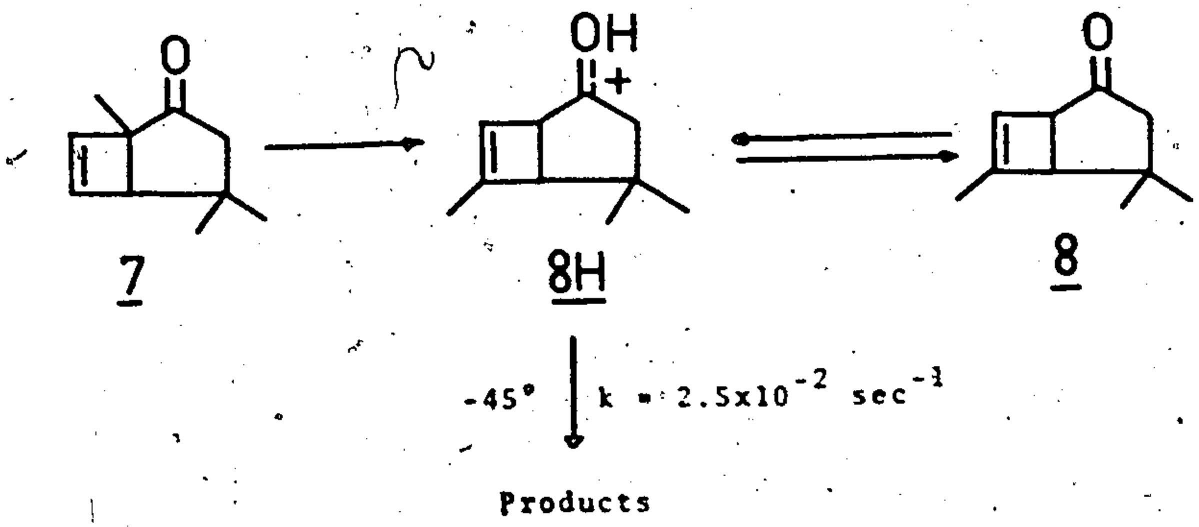
The ratio of 11H to 13H did not change during the course of these irradiations and prolonged photolysis of the product mixture did not result in decomposition or formation of additional products. However, independent experiments on 11H demonstrated that it could be isomerized to 13H either thermally ($t_{\frac{1}{2}}$ = 16 min at -15°) or photochemically by irradiation through a pyrex filter, $\lambda > 280$ nm. At this time it must be emphasized that under those conditions used for isomerization of 6H, 11H was stable to rearrangement. In addition, any product formed which comprised less than 5% of the final mixture normally would not be detected in these latter experiments as all analyses were performed by pmr spectroscopy.

The results shown in Figure 13 would strongly indicate that photoisomerization of protonated eucarvone, in contrast to that of neutral eucarvone, does not produce 7 or any cation corresponding to it. To reinforce this point, it was absolutely necessary to investigate the thermal stability of 7 (and 8, 9, 10, 12) in FSO_3H under the irradiation conditions. In addition it was imperative to establish whether 14H was a primary photoproduct of 6H or a thermal product of 7 - 12.

(iii) Thermal Stability of 7, 8, 9, 10, and 12 in FSO_3H

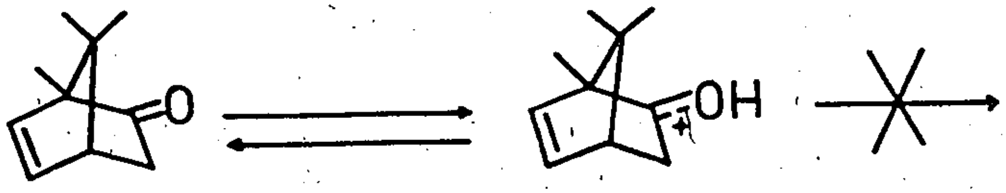
The ketones needed for this study were obtained from the irradiation of eucarvone according to the procedures of Hart[52] and Hurst and Whitham[45]. Identification of these compounds was made on the basis of their pmr (Table 5) and ir (experimental section) spectra in comparison to those previously reported. All compounds used were greater than 95% pure (glpc analysis).

Protonation of 7 at -120° in SO_2ClF : FSO_3H (2:1 $^v/v$) gave a pale yellow solution whose pmr spectrum, Table 5, at -85° was identical to that obtained via protonation of 8 under analogous conditions. At -60° 8H remained unchanged for an hour but at temperatures greater than -45° rapid isomerization took place to what appeared to be a



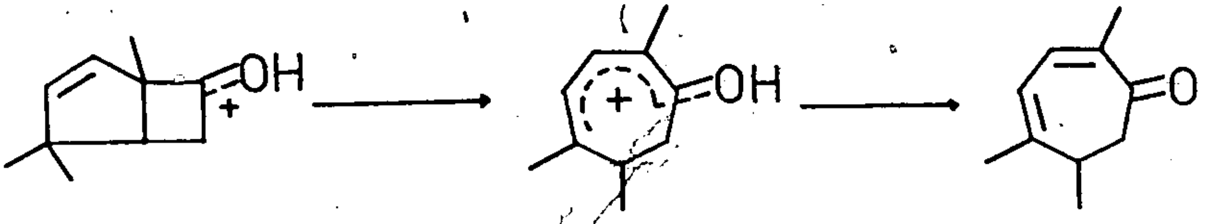
mixture of cations. The pmr signals of this mixture were quite distinct and were definitely not observed upon irradiation of 6H. Neutralization at -45° gave an oil, which glpc analysis showed that it consisted of three volatile compounds in the ratio of 1:1:8. The glpc retention times of these products were dissimilar to those of 11, 13, and 14 under identical conditions. Identification of these compounds was not pursued further. It was clear that 7H or 8H were not produced from 6H.

Dehydrocamphor, 10, dissolved in FSO_3H at -78° to give 10H. Neither heating (1 hr, -25°) nor irradiating (6 hr, $\lambda > 280$ nm) solutions of 10H caused any change in the pmr spectrum. Quenching this solution recovered 10 in high yield.



10 10H

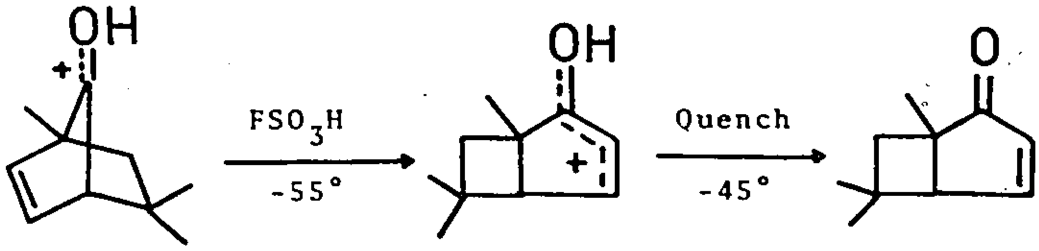
The cyclobutanone, 12, readily dissolved in FSO_3H or $SO_2ClF:FSO_3H$ (2:1) at -78° to give 12H which rearranged at -55°, $k = 7\times10^{-4}sec^{-1}$, to one product whose pmr spectrum was consistent with the protonated cyclohepta-2,4-dienone 16H. This acid solution was quenched to give an oil whose ir, $\nu_{c=0}$ = 1665 cm^{-1} and uv, $\lambda_{max}^{CH_3OH}$ = 310 nm, log ε = 3.7, suggested a cyclohepta-2,4-dienone. Further support for this mode of reaction was provided by the observation that the parent cation, 12′, rearranged in $FSO_3H:SO_2ClF$ at -75° to give, exclusively, protonated cyclohepta-2,4-dienone.[63]



12H 16H 16

12′

Of paramount importance was the observation that 9H quantitatively isomerized to 14H in FSO_3H at -55° ($t_{\frac{1}{2}}$ = 10-15 min). The identity of 14H was secured beyond all reasonable doubt by comparing the spectral properties of this product with those of 14H (and 14) obtained from 6H. Since it appeared that 9H and not 14H could be the primary photoproduct of 6H, small quantities (3-4 mg) of 6 were irradiated in FSO_3H at ≤ -75° for 15 minutes. The resultant



9H 14H 14

solutions were quenched extremely carefully at -65° and analyzed by glpc. It was observed that the oil consisted of 9 (1.5%), 14 (0.5%), 6 (50%), 11 (40%) and 13 (8%) on the basis of retention times. To be certain of 9, small quantities of authentic material were added to this mixture. Subsequent analysis revealed an increase in the relative amount of 9, and in addition the glpc peak corresponding to this product remained uniform under conditions which doubled its retention time. When these small scale irradiations were repeated but allowed to warm up to -45° for ca. 15 minutes before quenching, glpc analysis showed 9 (<0.5%), 14 (2%), 6 (50%), 11 (40%), 13 (8%).

In summary, it can be unequivocally stated that only 11, 13, and 9 are the primary photoproducts of protonated eucarvone, Figure 14.

Figure 14. Primary Photoproducts of Protonated Eucarvone

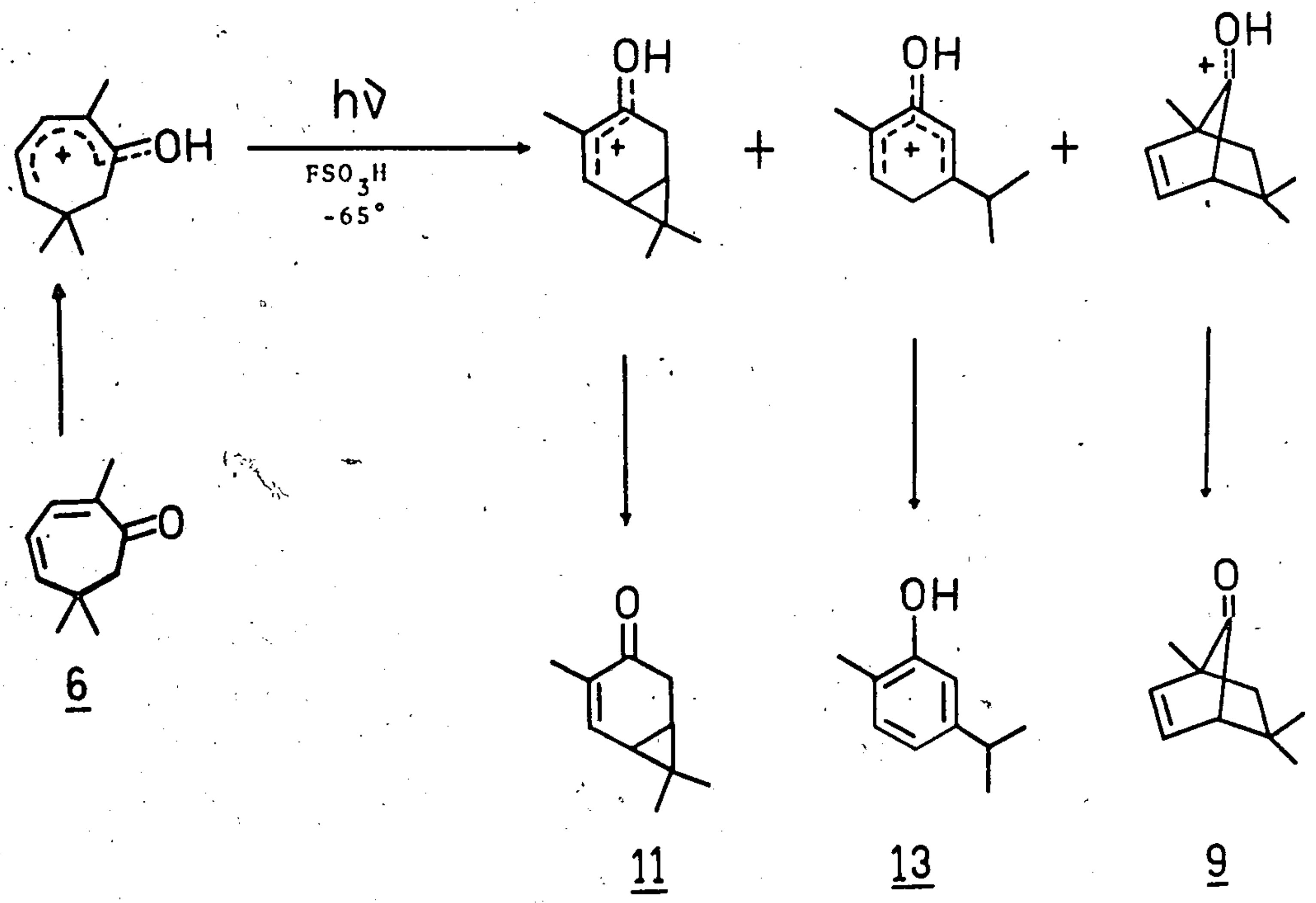


TABLE 5. Pmr Spectra of Eucarvone Photoproducts and their Corresponding Cations[a]

Compd	H_1	H_2	H_3	H_4	H_5	H_6	H_7	Methyls	Coupling Constants[b]
7	—	—	8.30 7.20	—	7.43	3.68	3.94	8.80,8.92,9.08	$J_{5,6} = 1.0$, $J_{6,7} = 2.8$, $J_{3,3'} = 17.0$
8	7.03	—	8.30 7.30	—	7.27	—	4.13	8.18,8.82,9.06	$J_{3,3'} = 16.0$
8H[c]	5.85	—	6.37 7.12	—	6.73	—	4.03	8.03,8.68,8.88	$J_{3,3'} = 22.0$
9	—	3.62	3.62	7.60	—	8.9	—	8.83,8.93,9.10	$J_{2,3} = 3.5$
9H[d]	—	3.30	3.30	6.71	—	8.14 8.39	—	8.60,8.83,8.94	$J_{2,3} = 2.7$, $J_{6,6'} = 12.2$
10	—	—	8.22 7.90	7.38	3.63	4.46	—	8.94,9.04,9.10	$J_{4,5} = 3.1$, $J_{5,6} = 5.8$, $J_{3,3'} = 16.4$
10H[e]	—	—	6.88	6.92	2.71	4.40	—	8.62,8.75,8.85	$J_{5,6} = 5.5$
12	7.92	—	4.47	4.68	—	—	6.94 7.28	8.75,8.86,8.88	$J_{3,4} = 5.5$, $J_{1,7} = 7.2$ $J_{7,7'} = 18.0$
12H[f]	n.o.[g]	—	4.44	3.84	—	—	n.o.[g]	8.26,8.70,8.70	$J_{3,4} = 5$

[a] At 100 MHz, ketones in CCl_4 (TMS), cations in $SO_2ClF:FSO_3H$ unless stated otherwise

[b] ± 0.3 Hz [c] at -55° [d] -70° [e] in FSO_3H at -25° [f] at -85° [g] not observed

(3) A RE-EXAMINATION OF EUCARVONE PHOTOCHEMISTRY

(i) Solvent Effects Upon Product Distribution

The results of the previous section in comparison to earlier studies of eucarvone photochemistry suggested a parallel between the photoisomerizations of protonated eucarvone and the neutral ketone. The major product resulting from a (π,π^*) state of 6H was shown to be identical to the product which was suggested by Hart to have arisen from a (π,π^*) state of 6.[51,52] In addition, both 6H and 6 yielded minor amounts of the compound 9, originally assumed by Hurst and Whitham[45] to have been produced from a protonated (π,π^*) state of the ketone. However, it seemed puzzling, in view of the formation of 11H from 6H, that no 11 was obtained from 6 in solvents such as acidic dioxane where proton transfer would certainly be important. At this stage, it was felt that a meaningful discussion of these results could be made only if a thorough knowledge of the products in aqueous acid was obtained.

Table 6 lists the results of a comprehensive study of solvent effects on product distribution. Reactions were carried out to < 5% completion to minimize the formation of the secondary products. Independent runs in methanol and aqueous acetic acid showed that irradiation of 7 yielded 8 and 11 yielded 10 and 12 as was previously reported.[52] In cases where small amounts of these products were produced

TABLE 6. Solvent Effects on Product Distribution[a]

Solv	Relative Percent		
	7	11	9
Ether	99	1	n.d. [b]
Methylene chloride	94	6	n.d.
Methanol	81	19	n.d.
90% Methanol - 10% H_2O	78	22	n.d.
80% Methanol - 20% H_2O	77	23	n.d.
70% Methanol - 30% H_2O	72	28	n.d.
95% Acetic Acid - 1% H_2O	76	22	2
75% Acetic Acid - 25% H_2O	69	24	7
60% Acetic Acid - 40% H_2O	63	28	9
96% Dioxane - 4% 1.8N H_2SO_4	71	6	23
Silica gel - Cyclohexane[c]	70	30	trace
Trifluoroethanol[c]	66	34	n.d.

[a] all irradiations at 350 nm through pyrex

[b] not detected ($<$ 0.5%)

[c] Hart's results, reference 52.

they are included in the relative percentage of 7 and 11. Glpc analyses were conducted only when the yield of recovered 6 and products was essentially quantitative, ≥98%. The numbers reported in Table 6 are the relative percent of products and were generally reproducible to ±2%.

There are a number of important observations from this study which must be pointed out.

(1) The formation of 9 occurred only in acidic solvents.

(2) The formation of 11 occurred in all solvents studied, including acidic and relatively non-polar ones. The results of Table 6 qualitatively indicate a gradual increase in the relative amount of 11 with solvent polarity. To obtain a somewhat more quantitative idea of this observation, a plot of Y verses percent 11 was drawn, Figure 15. The graph shows a straight line correlation between the amount of 11 and an established measure of solvent polarity.[64]

(3) The results obtained in strongly polar, hydrogen bonding solvents were identical to those reported by Hart.[52] (See Table 6 for Hart's results.)

In preparative scale runs additional minor products (10%) were obtained after prolonged photolysis of eucarvone and the reaction product mixture. For example, after ca. 50% reaction of 6, three ketones $\nu_{c=0}$ = 1780, 1700, and 1675 cm^{-1} and a phenol $\nu_{c=0}$ = 3600 cm^{-1} (<1%) were isolated by glpc. The ir spectrum of the latter compound was identical

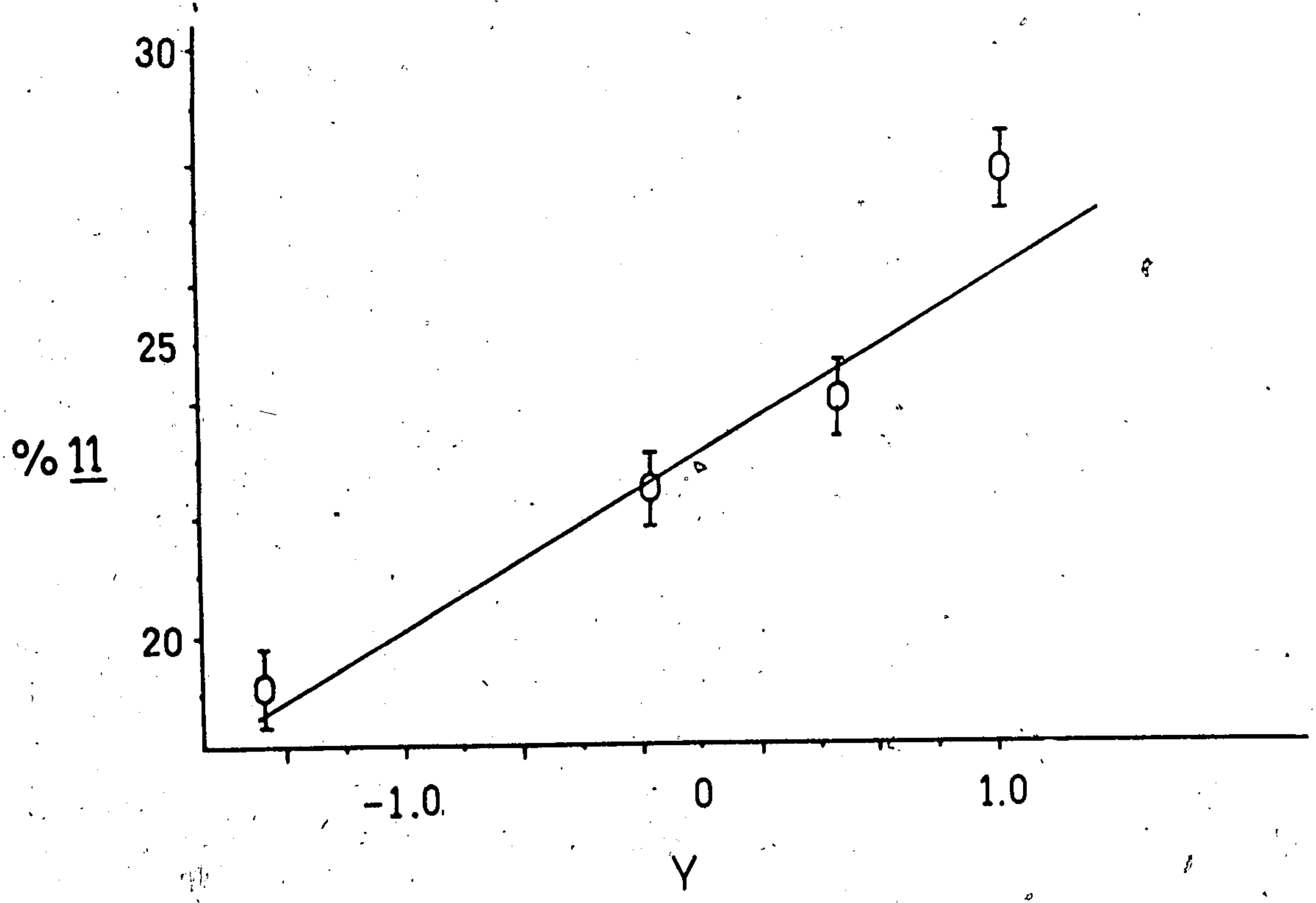
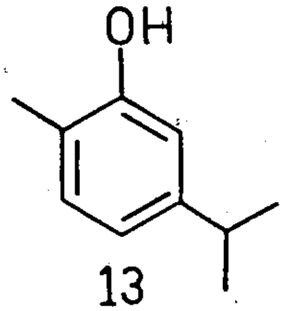


Figure 15. Relative Percent 11 verses Y

to that of carvacrol, 13.

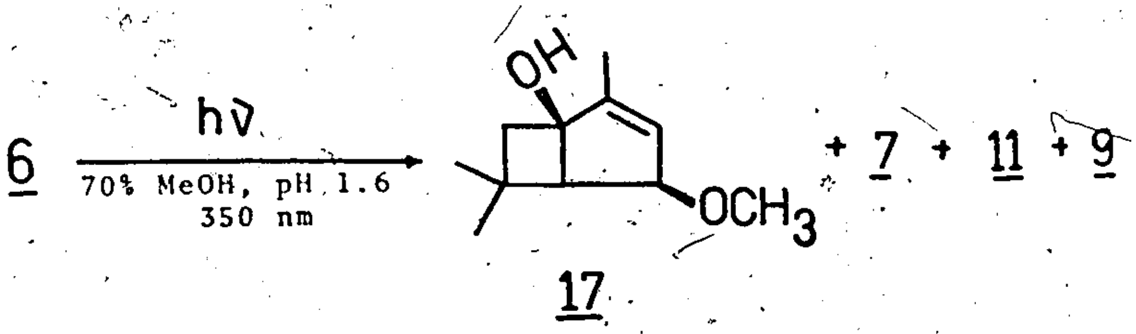


13

The results of Table 6, albeit important, do not provide any evidence concerning possible relationships between the photoproducts in acidic media. For instance, it could not be established whether 9 originated independently of 11 or 7 or whether its formation had a direct relationship to either of these primary products. To more systematically probe the effect of solvent acidity upon the photoisomerization of eucaryone, product studies were made in a series of buffered solutions of constant polarity.

(ii) Photoisomerization of Eucarvone in Buffered Solvents

These buffer solutions were prepared by diluting 30.0 ml of standard aqueous phosphate buffers with 70.0 ml of methanol according to a procedure analogous to that reported by Zimmerman.[41] The pH reported below, and later in Table 7, was recorded after dilution. Exploratory irradiations of 6 in solutions of pH 1.6 gave, in addition to those products obtained in 60% acetic acid, a new photoproduct which consistently comprised 20-25% of the product mixture. It was collected by preparative glpc as a clear, colourless oil and assigned the structure 17 on spectral, analytical, and chemical evidence. The structure of this photoproduct is sufficiently significant to rate detailed attention at this time.



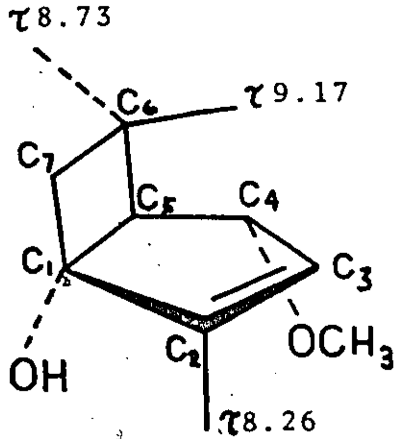
(a) Identification of the New Photoproduct

The mass spectrum ($^{m}/e = 182$) and elemental analysis (% C = 72.28, % H = 9.81), indicative of the formula $C_{11}H_{18}O_2$, suggested an addition of methanol to the elements of eucarvone. Its uv spectrum was featureless above 220 nm and the ir spectrum displayed a broad, intense band between 3550 cm^{-1} and 3150 cm^{-1} but no carbonyl absorption. Taken together, the data suggests a bicyclic methoxy alcohol.

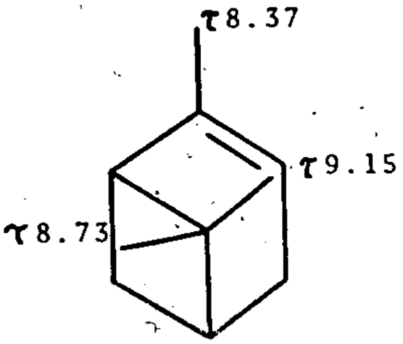
The pmr spectrum was fully consistent with the assigned structure. Four sharp singlets, each three protons, implied methyls. Those at τ 6.87 and τ 8.26 are characteristic of a methoxy group and vinyl methyl respectively. The two high field singlets were assigned to the aliphatic gem-dimethyls on C_6. One vinylic hydrogen at τ 4.43 was shown by decoupling experiments to be coupled to the C_2 methyl, J = 1.7 Hz. The C_4 allyl proton was a broad singlet at τ 6.17 which was shown to be coupled to the vinyl hydrogen, J = 1 Hz, but not to the bridgehead, C_5 proton, at τ 7.91, J ≤ 0.5 Hz. The remainder of the spectrum consisted of the hydroxy proton as a singlet at τ 6.80 and the geminal C_7 hydrogens as an AB quartet τ 8.08 and τ 8.33, J = 12.0 Hz.

One reasonable explanation for the difference in chemical shift of the C_6 methyls can be formulated through a consideration of shielding effects of the double bond. An inspection of a molecular model of 17 revealed that one methyl was positioned closely above the π-electron cloud of the olefinic bond. This group, which would experience a shielding influence,[65] was assigned to the higher field singlet at τ 9.17. Quite similar effects have been reported for the geminal methyls of the α-pinene system 18.[65] The shielded methyl group in this case is located at τ 9.15, close to the corresponding one in 17. Remarkably enough, the other methyl of this gem-dimethyl group in α-pinene has exactly the same chemical shift as its analogue in 17.

The stereochemistry of the C_4 methoxy group has

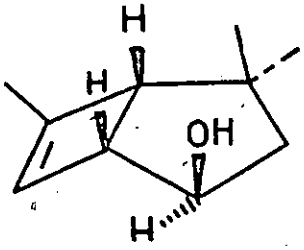


17

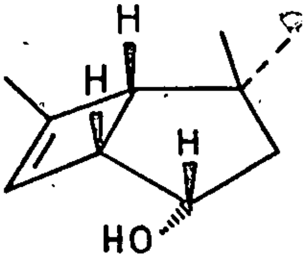


α-PINENE

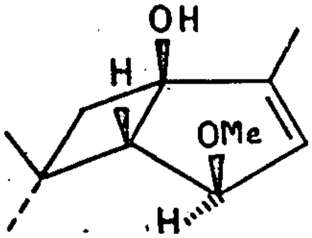
been assigned as syn to the hydroxy group at C_1 based upon the small value, ≤ 0.5 Hz, of the vicinal $J_{4,5}$ coupling constant. According to the Karplus rule, this value corresponds roughly to an angle of 90° between the C_4H and C_5H bonds.[66] Inspection of a model of 17 would place this angle at 100 $\pm 5°$. If the methoxy group were anti to the hydroxy group, the model revealed that the vicinal angle would be ca. 0° and correspondingly, a non-zero coupling constant would be predicted. Some idea of the magnitude of this coupling constant can be obtained from the study of the pmr spectra of the bicyclo[3.2.0]hept-6-en-2-ols 19a and 19b reported by Whitham in 1967.[67] In 19a the C_1H-C_2H angle, as in the case of 17, is ca. 90°-100° and it was reported that "no apparent coupling" occurred between the C_2 and C_1 protons. On the other hand when this angle is decreased to about 0° as in 19b, the C_1H-C_2H coupling constant was reported to be 9.4 Hz. Quite similar results were obtained for the related bicyclo[3.2.0]heptenone system and some simple derivatives.[68,69]



19a



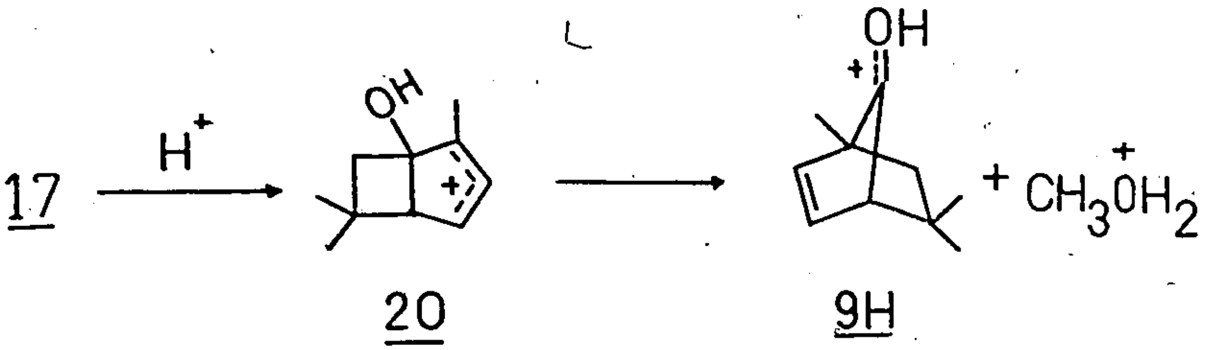
19b



17

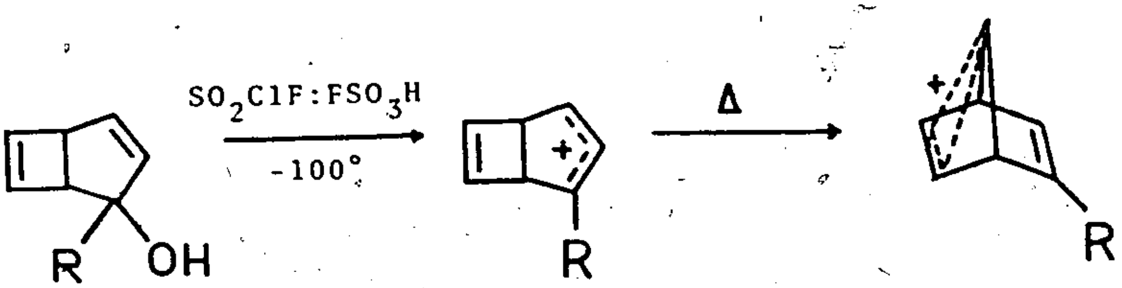
Strong supportive evidence for the spectral assignment of 17 and its relationship to 9 was provided by the reaction of 17 in acid. Solution of 17 in $SO_2ClF:FSO_3H$ (2:1) at -110° followed by examination by pmr four minutes later at -75° showed that 17 had completely reacted to give only 9H plus protonated methanol. The identity of 9H was secured by comparing its pmr spectrum to that of authentic 9H and observing its known rearrangement to 14H at -55°, Figure 16. Protonated methanol was observed as a three proton singlet at τ 4.20. This is close to the value found for methanol in FSO_3H at -55°, τ 4.32, and reasonably near to the reported[70] chemical shift of the methyl group in $FSO_3H-SbF_5-SO_2$ at -60°, τ = 4.70. Similarly, when 17 was refluxed in pH 0.7

Figure 16. Thermal Isomerization of Photoproduct 17 in Acid



buffer solution for 45 minutes it was converted to 9.

The reaction of 17 to 9 can be viewed as occurring via protonation on oxygen of the methoxy group, elimination of methanol to give the intermediate 20, followed by a 1,2-alkyl shift as shown above. There exists ample precedent for this mechanism and the invocation of the cationic ~~intermediate 20.~~ For example, Winstein and coworkers have observed the direct isomerization of the bicyclo[3.2.0]heptadienyl cations 21 to the 7-norbornadienyl systems, 22, by pmr at low temperatures.[71] The reaction of the proposed intermediate 20 would be expected to occur at a rate comparably rapid relative to those shown for 21. In 9H, stabilization of the positive charge could be accomplished not only via a homoallylic interaction as in 22, but also by placing the charge on a carbon adjacent to a hydroxy function.[72,73] Reaction of 17 to 9 in weaker acid systems is quite analogous to the solvolysis of the para-toluenesulphonate derivatives of 19a and 19b to the corresponding bicyclo[2.2.1]hept-2-en-7-acetates.[67] The relationship of 17 to 9 quite strongly suggests that the former is produced in the irradiations of 6 via a nucleophilic capture by methanol of an intermediate leading to 9. This intermediate may structurally be very similar to 20.



21

22

Rate of Isomerization of 21[71]

R	Temp (°C)	k (sec^{-1})
H	-120°	$k = 1\times10^{-2}$
CH_3	-105°	$k = 2.0\times10^{-4}$

In control experiments it was shown that 17 did not arise from 7, 9, or 11 under the irradiation conditions. Compound 9 was thermally and photochemically stable; compound 7 gave 8 either by irradiating or heating solutions of 7. No decomposition or thermal isomerization of eucarvone could be detected by pmr spectroscopy upon heating solutions (pH 1.62) of 6 for 22 hr at +60°.

(b) Effects of Solvent Acidity on Product Distribution

One percent solutions of 6 in the methanolic buffers were irradiated at 350 nm in a merry-go-round apparatus to insure equal exposure to all samples. The products and unreacted 6 were recovered in >96% yield and analyzed by glpc. Using chlorobenzene as internal standard it was determined that no products escaped detection. Table 7 lists the product distribution as a function of the apparent pH. These results indicate that the formation of 9 and 17 occurs only in relatively acidic solutions at the exclusive expense of photoproduct 7. Neither the rate of disappearance of 6 nor the rate of formation of 11 was affected by acidity within the limits of detection, ±2%. Quite clearly, the formation of 11 is independent of those pathways leading to 7, 9, and 17.

TABLE 7. Product Distribution as a Function of Solvent Acidity

pH	Recovery %	Conversion %	Product Ratios[a]			
			7[b]	9	11[b]	17
6.16	98	9.5	73	n.d.[c]	27	n.d.
3.34	98	8.5	70	0.5	29	0.5
1.62	100	8.5	53	2	27	18
0.7	97	8.5	45	4	28	23
d	96	—	72	n.d.[e]	28	n.d.[e]

[a] expressed as relative percent

[b] total percent includes photoproducts of 7 and 11

[c] < 0.5%

[d] 70% CH_3OH -30% H_2O as solvent

[e] not detected

(4) QUENCHING STUDIES

A number of experiments were performed using cyclohexa-1,3-diene and piperylene as quenchers in acidic solvents to obtain some information concerning the multiplicity of the excited state of 6 involved in the production of 9 and 17. The results are shown in Tables 8, 9, and 10 and Figure 17. Their significance is discussed in the next section.

TABLE 8. Quenching Results in 96% dioxane-4% water[a]

[Q] m.l.$^{-1}$	Φ_o/Φ [b,c]
0	1.00
0.0025	1.13
0.005	1.14
0.0094	1.30
0.0175	1.33
0.0294	1.39
0.055	1.52

[a] using cyclohexa-1,3-diene, at 350 nm

[b] measured after 2% reaction

[c] ratio of <u>7</u> to internal cycloheptanone measured by glpc analysis ± 2%.

Figure 17. Relative Quantum Yield for the Formation of 7 in 96% Dioxane - 4% H_2O as a Function of Cyclohexa-1,3-diene Concentration

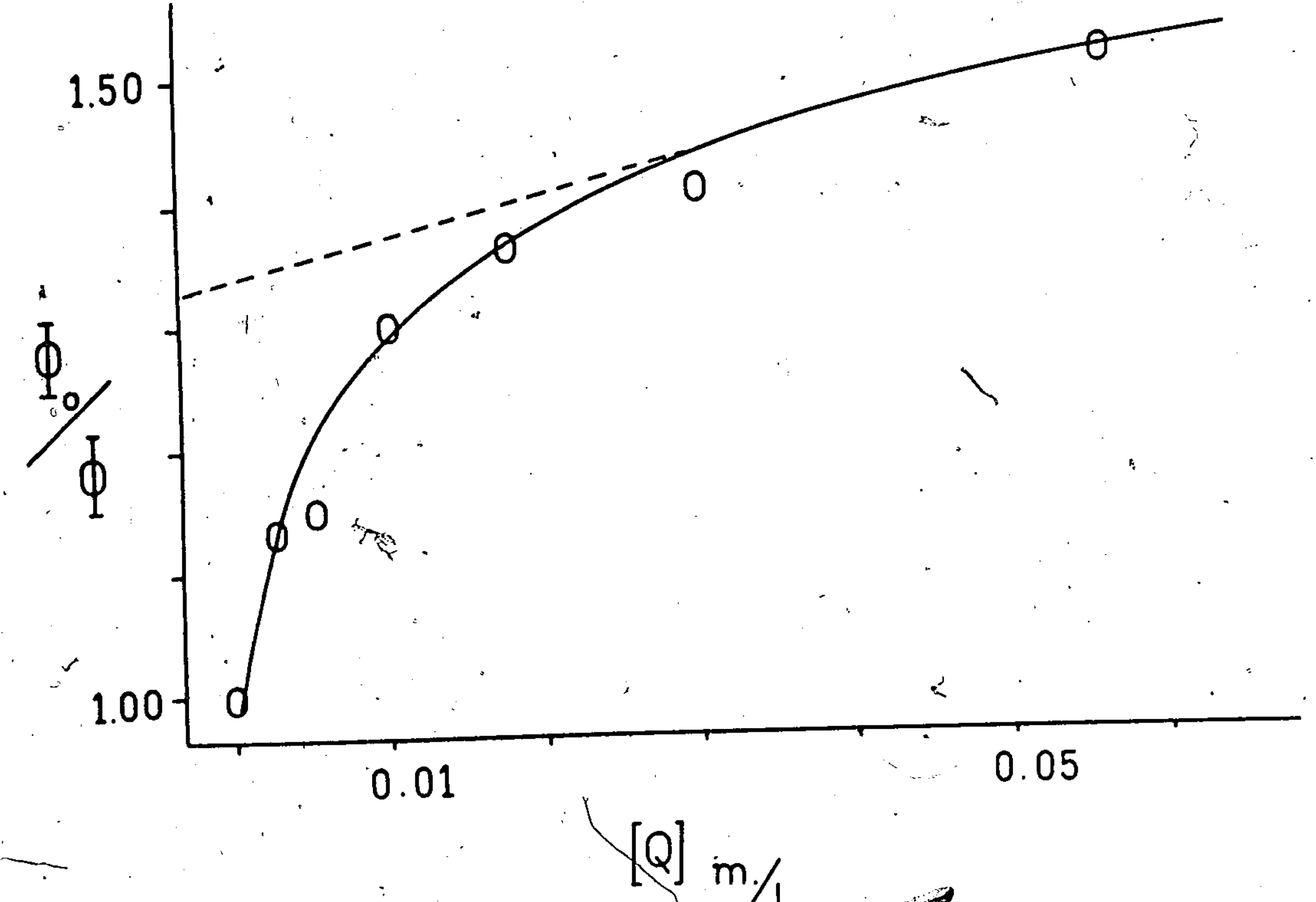


TABLE 9. Effects of 0.05 M piperylene on Product Ratios[a]

[Q] m.l.$^{-1}$	% reaction[b]	% recovery	Relative %[c]		
			9 + 17	7	11
0	11	96	18.4	48.3	33.3
0.05	29	—	19.5	45.3	35.2

[a] in pH 1.6, at 350 nm.

[b] % 6 relative to products

[c] ± 2%

TABLE 10. Effects of Cyclohexa-1,3-diene in Acidic Dioxane[a]

[Q] m.l.$^{-1}$	Relative %[b,c] 9	7
0	25.8	74.2
0.0065	26.5	73.5
0.0082	26.2	73.8
0.0113	24.0	76.0
0.0298	24.0	76.0
0.0537	26.0	74.0

[a] 96% H_2SO_4 - 4% 1.8N H_2SO_4 at 350 nm

[b] glpc analysis ± 2%, 9 and 7 comprised 95% of the product mixture, 5% was 11

[c] % recovery in each case was 80-85%.

(5) DISCUSSION: THE RELATIONSHIP BETWEEN THE PHOTOISOMERIZATION OF EUCARVONE AND PROTONATED EUCARVONE

The results of the previous sections have demonstrated that one can obtain identical products by irradiating a ketone in polar, acidic solvents or the corresponding protonated ketones in FSO_3H. There can be only two a priori reasonable and chemically rational explanations for this observation. On the one hand it might be considered that the reactant in each case is the same. Alternatively, the reactive excited states and/or intermediates bear a close relationship.

If we examine the nature of eucarvone in aqueous methanol or acetic acid verses fluorosulphuric acid, little support for the first proposal can be gained. Both the uv and pmr spectra in these solvents indicate that in one case the ketone is being irradiated and in the other only the protonated ketone is the reactive species. Upon excitation of 6 an excited state is reached which reacts to give 11. This state must be of a similar nature as that derived from protonated eucarvone.

It was originally suggested by Hart that the formation of 11 from 6 most reasonably occurred from a (π,π^*) state whose energy was sufficiently lowered by polar media to permit significant population upon excitation of 6. Considering the red shift of the (π,π^*) absorption band of eucarvone in silica-gel-cyclohexane, this would appear to be a reasonable assertion. There exists abundant evidence in the form of spectroscopic studies on analogous ketones which suggests an energy lowering of the (π,π^*) excited states under these conditions of solvent polarity.[74] As well, the solvent acidity is not an important feature for the production of 11 since only ca. 6% of this product was obtained in 96% dioxane-4% 1.8N H_2SO_4 compared to 30% in the comparably acidic but more polar acidic aqueous methanol solvents.

Nonetheless, one problem which Hart was unable to resolve concerned the formation of about 70% photoproduct 7 from 6 in these polar solvents. The data which he could obtain from his study did not provide evidence to indicate whether it arose from the same state as 11 or from one close in energy, possibly (n,π^*). The study of the photochemistry of protonated eucarvone can provide an answer to this question. Since it reacts exclusively via π-π^* excitation, no ambiguity can arise over the nature of the excited state involved in the production of 11H (or 11). Thus, by extrapolating these results to those of neutral eucarvone we may conclude that 11 and 7 are formed from different excited states, the latter from an (n,π^*) and the former from an (π,π^*) state.

In FSO_3H, the energy difference between the (π,π^*) and (n,π^*) excited states is of sufficient magnitude that population of, and subsequent reaction from, only the lower energy (π,π^*) state occurs upon excitation. Clearly, the use of this solvent system as a means of perturbing the relative energies of these states is far superior to alcohol-water mixtures or silica-gel slurries wherein the excited states have comparable energies.

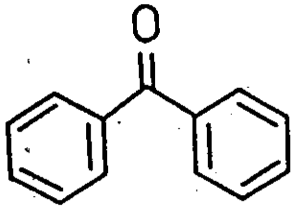
The assertion that a relationship exists between the (π,π^*) states of a ketone and a protonated ketone is not considered unjustified. In an elegant study, Leermakers has shown that a marked change in the nature of the lowest excited state of benzophenone takes place when subjected to extremes of solvent acidity and polarity.[33] The increase in the phosphorescence lifetime and the decrease in the wavelength of the phosphorescence band, Table 11, is consistent with a change from an $(n,\pi^*)^3$ to a $(\pi,\pi^*)^3$ with solvent polarity and acidity. The enhanced (π,π^*) character of the triplet is also displayed by the loss of vibrational structure of these emission bands. Similar type of results for the fluorescence and absorption spectra suggest comparable changes for the singlet states as well.

TABLE 11. Phosphorescence Data for Benzophenone[33]

Solv	τ_p (sec)[a]	λ(nm)
Methylcyclohexane (MCH)	0.005	390
Ether-Pentane-Alcohol	0.006	390
Ethylene glycol-water	0.077	385
Silica-gel-MCH	0.12	380
85% H_3PO_4	0.66	375
70% $HClO_4$	0.95	432
70% H_2SO_4	1.03	432

[a] Measured at 77° K

When the effects of solvent on the relative amount of 11 produced were examined it was found that the relative percent of this product increased proportionally with the polarity of the solvent. Such an observation is formally analogous to Leermakers' results for benzophenone.



benzophenone

Eucarvone reacts from a "protonated" excited state in FSO_3H in the sense that a proton is bonded to the carbonyl oxygen. It is interesting, however, to note that 11 is formed from 6 with equal facility in acidic or neutral media of comparable polarity. In this case, protonation would not appear to be a necessary step in the reaction of 6 to 11 and it is quite reasonable that zwitterionic intermediates, as advanced by Hart[52], could be involved. These results suggest that one of the controlling factors for this reaction is the electron deficiency of the π system of 6 or subsequent intermediates and not the nature of the charge on oxygen. However, as shall be pointed out in a subsequent section concerning mechanism (III-4), the charge on oxygen most probably determines the amount of carvacrol 13 produced from the (π,π^*) state of 6.

It would appear that the photoisomerization of protonated eucarvone could serve as a model for the (π,π^*) chemistry of the neutral ketone. Nevertheless, if the results of 6H can be meaningfully extrapolated to those of 6, one must be able to accommodate the formation of 13H and 9H in strong acid. The obvious relationship between 13H and 11H suggests that both could arise from a common intermediate. Discussion of this point is best reserved until the results of some mechanistic experiments have been described in the next section. However, the formation of 9H from 6H would seem to be somewhat incongruous. The strong acid results imply that both 11H and 9H arise from a (π,π^*) state, yet the production of 9 (and 17) from 6 was demonstrated to take place at the exclusive expense of 7, an (n,π^*) product. We can obtain a rationale for this apparent contradiction by considering the nature of the reaction to 9 in more detail.

Schuster had reported that in benzene 7 is derived 60% from a singlet state of 6 and 40% from a triplet on the basis of quenching experiments with cyclohexa-1,3-diene and piperylene.[44] From the slope of the triplet portion of the

Stern-Volmer plot he calculated that the lifetime of the triplet was 7.6x10^{-8} sec. Rate constants for the isomerization and decay of this state were calculated to be 1.4x10^{4} sec^{-1} and 1.3x10^{7} sec^{-1}, respectively, from the quantum yield of 1.03x10^{-3} for the triplet reaction. Schuster also suggested that the lowest triplet would have a (π,π^*) configuration on the basis of the absorption spectrum of eucarvone. No definite evidence such as spectroscopic data was available to support this view.

Under the conditions specified in Table 7, where neutral eucarvone was absorbing all irradiation, about 20-25% of 7 could be diverted to 9 and 17 in acidic media. One reasonable explanation for the formation of these products is that protonation of the presumed (π,π^*)^3 of 6 may occur before reacting to 7 and ultimately produce 9 and 17. To test this proposal, shown below, some studies were conducted to ascertain whether a triplet of eucarvone could be involved in acidic solvents.

Possible Relationship between the Formation of 7 and 9

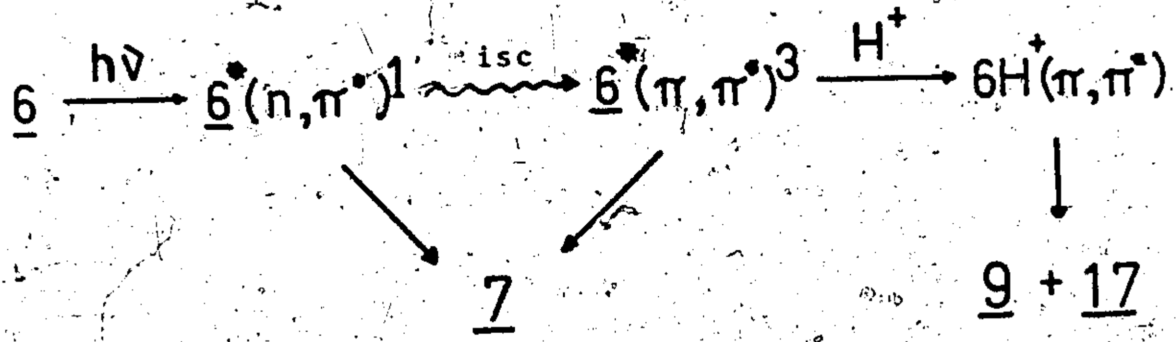


Table 6 indicated that 23% of 9 is formed in 96% dioxane-4% 1.8N H_2SO_4. Quenching studies were carried out initially in neutral 96% dioxane-4% water. The results with cyclohexa-1,3-diene as quencher, using internal cycloheptanone as a standard, are shown in Table 8 and in the Stern-Volmer plot, Figure 17. The effects of triplet quenchers in this solvent, although small, are consistent with efficient quenching of a triplet state at low diene-concentrations and perhaps a singlet at higher concentrations.[75] One conclusion from these results is that formation of 7 can occur from both singlet and triplet states of 6. By extrapolating the straight line portion to zero diene concentration, one can obtain a value for the amount of triplet contribution to the reaction; in this case it appears to be ca. 30%. These results are close to those reported by Schuster.[44] Thus, since a triplet state of 6 is implicated in the formation of 7 in neutral dioxane, it is possible that protonation of this state could give rise to 9 in acidic dioxane. Interestingly enough, the amount of 9 produced, 23%, is close to the amount of triplet contribution to the formation of 7.

Attempts were made to observe quenching of 9 and 17. In buffer solution pH1.6, 0.05 M piperylene had no effect upon the product ratios but did appear to accelerate the rate of disappearance of eucarvone, Table 9.

Similarly the ratio of 7:9 was unaffected over a quencher concentration range of ten in acidic dioxane, Table 10. For both cases, the concentration of diene was kept low to preclude any possibility of singlet quenching.

The lack of quenching in acid might appear to discount triplet state protonation in the formation of 9 and 17. However, proton transfer to excited states can be extremely fast reactions, $k \geq 10^{10}$ sec^{-1}, and could conceiveably complete effectively with energy transfer to dienes, which takes place at, or close to, diffusion controlled rates, $k = 10^9 - 10^{10}$ sec^{-1}.[1a,76] Protonation of this state may lower its energy to the point where energy transfer to cyclohexa-1,3-diene (E_t = 54 kcal/mole)[1c] is endothermic. Thus, attempts were made to observe phosphorescence from eucarvone to obtain some information of this possible energy change upon protonation. However, as in the case of most other simple dienones, no emission could be seen from eucarvone at 77°K in 1:1 ether-ethanol or 96% H_2SO_4. Nevertheless, we can get some idea of the triplet energy lowering from related work on benzophenone.

Leermakers reported a shift of the near edge of the phosphorescence band from 385 nm in ethylene-glycol-water to 432 nm in 98% H_2SO_4.[33] Using the relationship shown in equation (1)[1b], one can calculate an energy lowering of 7.2 kcal/mole. If we assume that a corresponding decrease could occur in the case of eucarvone, then upon protonation

$$E(\text{kcal/mole}) = \frac{2.86\times10^4}{(\text{m}\mu)} \qquad (1)$$

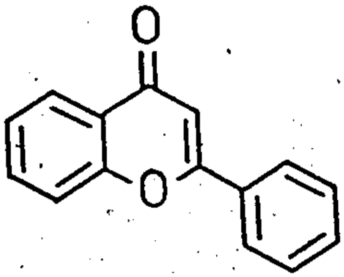
the energy will be lowered from 61±1 kcal/mole[44] to ca. 54-55 kcal/mole. This value is comparable to the triplet energy of the dienes. In order to observe quenching the energy of the donor must be at least 3 kcal/mole higher than the acceptor.

Some effort was made to measure the basicity of excited state eucarvone using the well-known Forster Cycle technique.[46,47] The relationship which is required is shown in equation (2). From this, one can obtain the excited state pKa having a knowledge of the 0-0 frequencies in absorption and emission from both the base form of the excited state and its protonated form. The lack of emission

$$pKa^{*} = pKa + \frac{0.625}{T}\left(\lambda^{-1}{}_{B} - \lambda^{-1}{}_{BH^{+}}\right) \qquad (2)$$

pKa^{*} = excited state pKa
pKa = ground state pKa
T = temperature
λ_B = 0-0 frequency of base form
λ_{BH^+} = 0-0 frequency of protonated form

from eucarvone precluded any calculations. Since numerous carbonyl compounds have been shown to experience large enhancements in basicity upon excitation,[46,47] it is not unreasonable to expect similar effects for eucarvone. Excited 6 may be sufficiently basic to be protonated in pH 0.7 or 1.6 solutions but not in pH $\geqslant$ 3.34. Flavone, for example, was shown to have a pKa* of 6.75. It fluoresced strongly from its unprotonated form in 0.001, 0.002, and 0.01 N hydrochloric acid and in a buffer of pH 6. In 2N H_2SO_4, the emission spectrum of it corresponded to that from a protonated state.[47c]



flavone

In conclusion, it is felt that the proposed scheme for 9 and 17 can explain their formation in acidic solvents at the exclusive expense of 7. It reasonably corroborates the results of protonated eucarvone where (π,π^*) states are certainly involved in the production of minor amounts of 9.

The next section of this thesis deals with the mechanism of the formation of 11, 13, and 9 from 6 and 6H. This part adds some fundamentally important knowledge to the understanding of cyclohepta-2,4-dienone photochemistry and further demonstrates the parallel between 6 and 6H.

PART 3 MECHANISTIC STUDIES

MECHANISTIC STUDIES

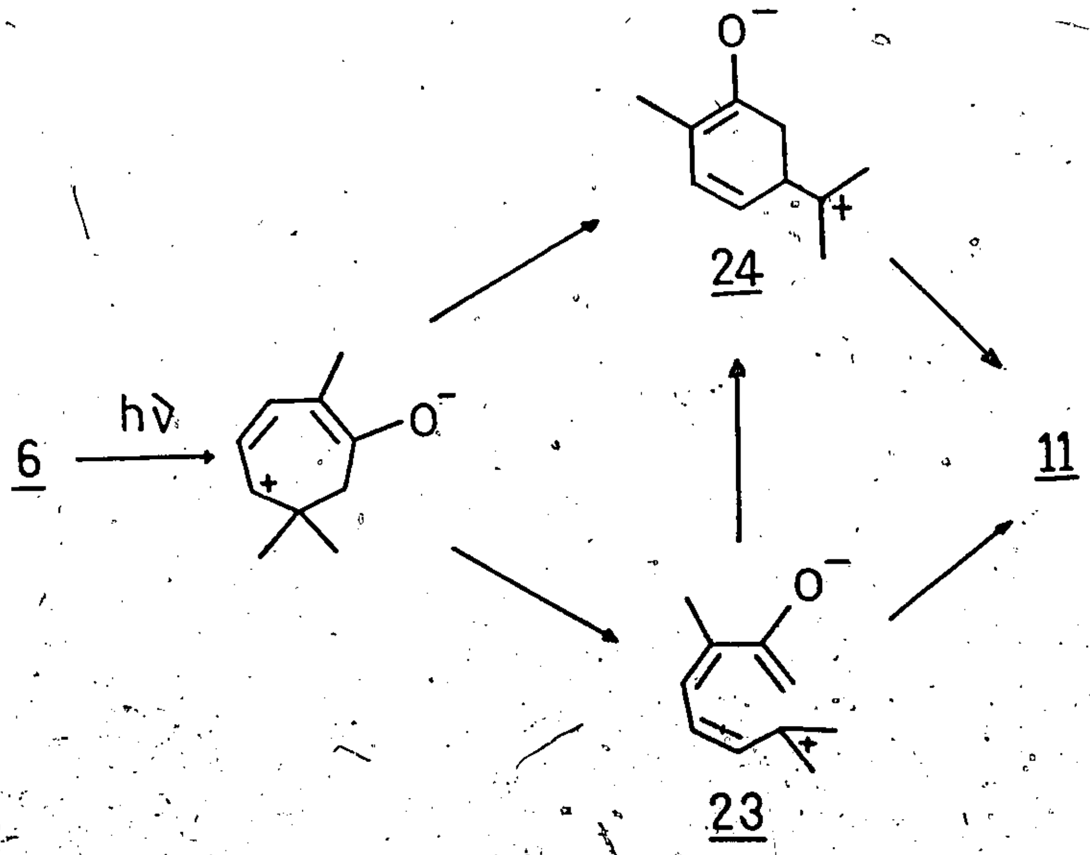
(1) INTRODUCTION

In the previous section of this thesis it was shown that the photoisomerization of protonated eucarvone produced a major photoproduct 11 which was identical ~~to that~~ formed from a (π,π^*) state of neutral eucarvone. At that time it was stated that the excited state precursors were of a similar nature and possibly could have reacted in an analogous fashion. In this part, some mechanistic aspects of these reactions will be described.

Hart proposed that the formation of 11 could take place either via a concerted $\sigma 2a+\pi 2a$ reaction or a stepwise pathway involving, perhaps, the zwitterionic intermediates 23 and 24 (Figure 18). He tentatively disfavoured the concerted reaction on the basis that 11 was formed only in polar media but could state little else on the available evidence.

Prior to Hart's publication it was independently recognized that the production of 11H from 6H could be described in a somewhat analogous fashion.[77] In simplest terms, this reaction involves initial rupture of the C_6-C_7 bond followed by bond formation between C_6 and C_4

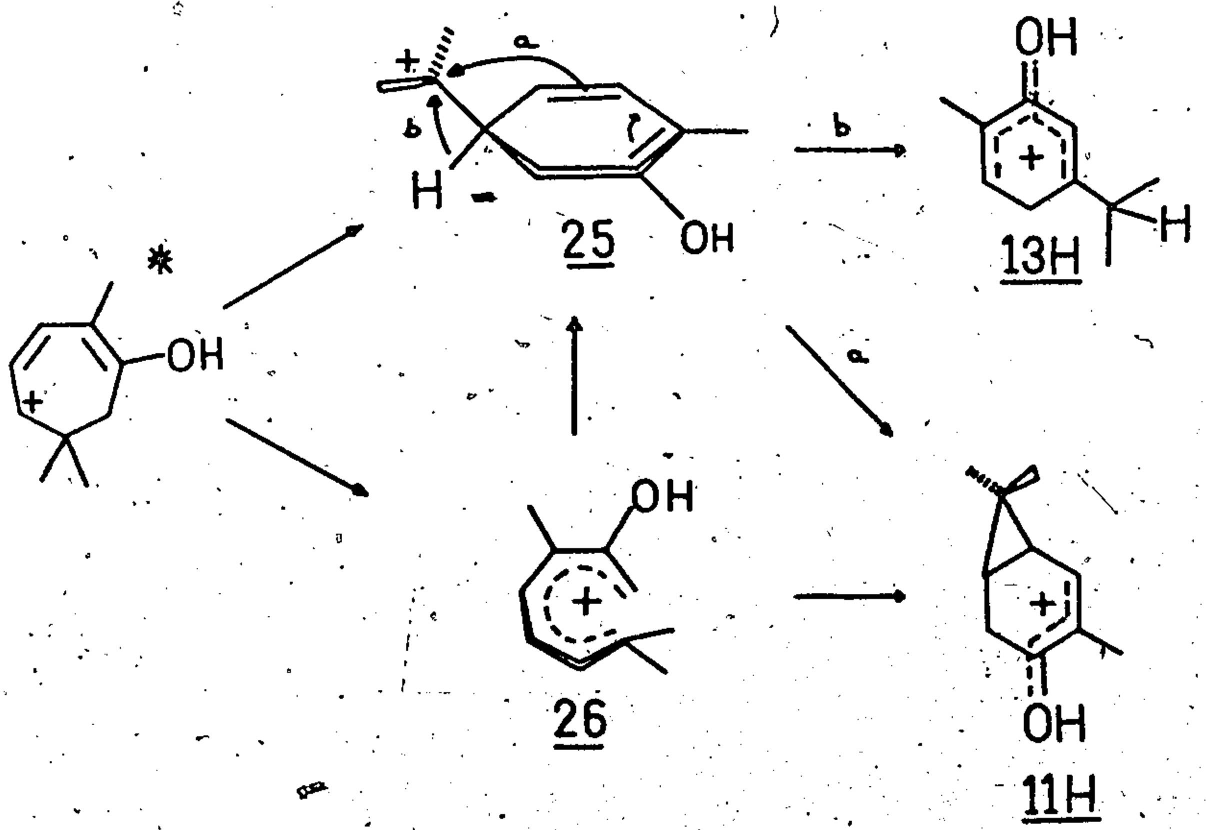
Figure 18. Hart's Proposed Mechanism for the Formation of <u>11</u>



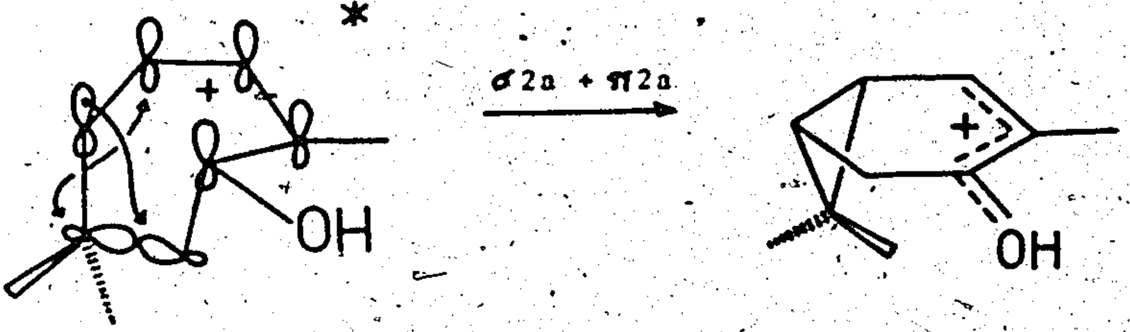
and C_7 and C_5. This process can take place in either a stepwise or concerted fashion as illustrated in Figure 19. The latter mechanistic possibility can be thought of as adding the electrons from the lowest unoccupied molecular orbital of the σ bond to the highest occupied molecular orbital of the pentadienyl system. When the reaction is photochemical, the tenets of orbital symmetry conservation dictate that this addition occurs in an antarafacial manner. Inversion of configuration takes place at C_6 and retention

Figure 19. Stepwise and Concerted Mechanism for the Formation of <u>11H</u>

STEPWISE



CONCERTED

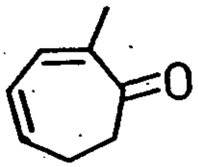


at C_7 with addition to the π system occurring from opposite directions. The alternate route involves formation of one, or perhaps two, intermediates which could react as shown in Figure 19. On the basis of available evidence no bias can be placed upon either pathway or upon the relative merits of 25 or 26.

However, one way to examine these possibilities would be to observe what effect the methyl substituents at C_6 would have upon the production of bicyclo[4.1.0]heptenones (i.e., 11 or 11H) from cyclohepta-2,4-dienones. For example, in the absence of stabilizing groups at this position, one would predict that an ionic intermediate described by 24 or 25 would be of relatively high energy since a primary carbonium ion is generated at C_6. As a result, one might expect that the rate of formation of compounds corresponding to 11 or 11H would be decreased in favour of other products. On the other hand, if open chain, delocalized cations were intermediates, or if a concerted mechanism were operative, the production of bicyclo[4.1.0] compounds should occur equally well from cyclohepta-2,4-dienones unsubstituted at C_6.

To study the effects of the gem-dimethyl system on the photoisomerizations of cyclohepta-2,4-dienones, the parent system 27 and its 2-methyl derivative 28 were synthesized and their photochemistry investigated.

27



28

(2) SUBSTITUENT EFFECTS

(i) The Photoisomerization of Cyclohepta-2,4-dienone

(a) In neutral and weakly acidic solvents

Compound 27 was prepared by a rather novel procedure described in the literature[78,79] and later in this thesis. Irradiation of 27 in neutral solvents such as ether or methanol produced only the isomeric bicyclo[3.2.0]hept-6-en-2-one, 29, Figure 20. The ir of this product had identical bands at 3050, 2960, 1735, 1270, 1163, 870, 862 cm^{-1} to those reported by Story for 29.[80] A detailed examination of its pmr spectrum, Table 12, in comparison to those of 7 and 8 added further support for the structure of this product. Subsequent to publication of this work,[81] Schuster reported the exclusive formation of 29 from 27 in a related photochemical study.[82] It must be emphasized that these investigations were conducted completely independent of one another.

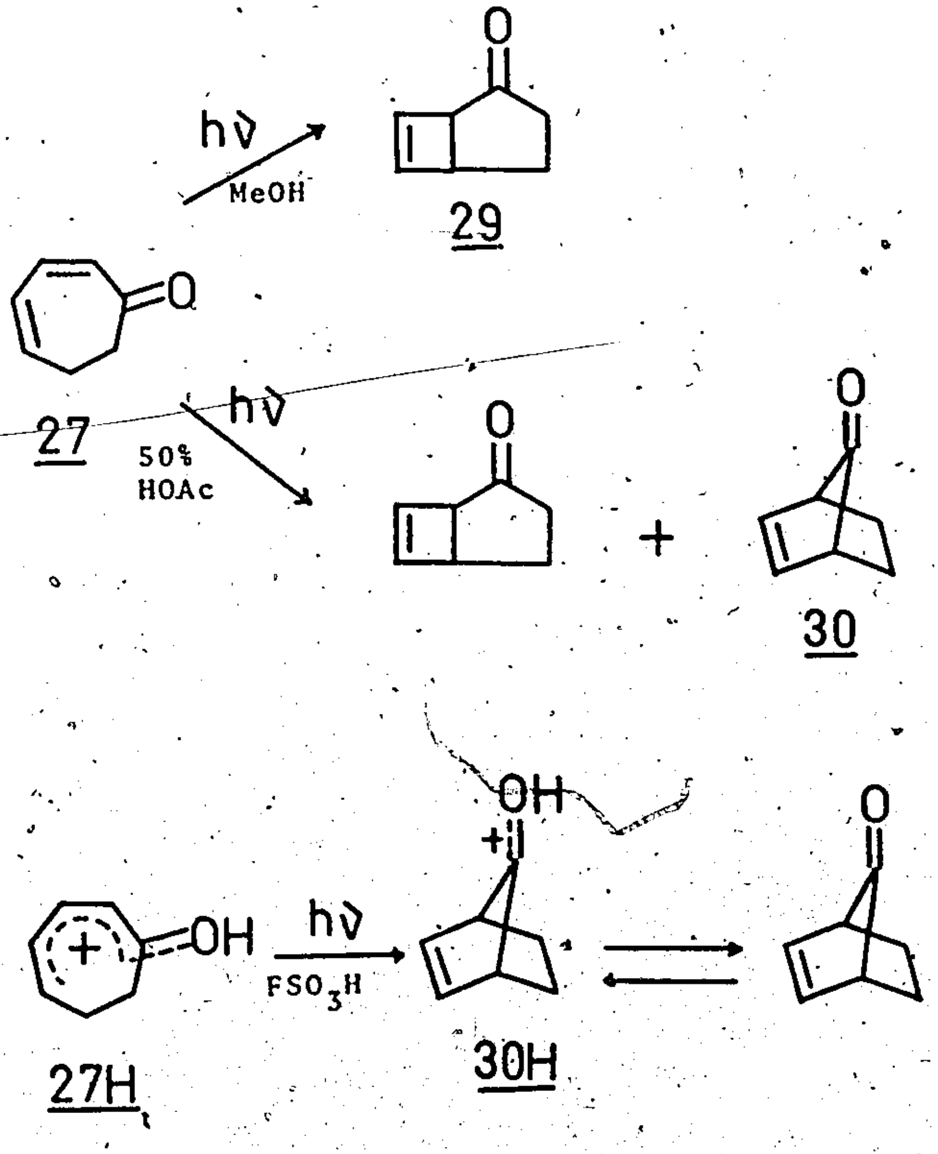
TABLE 12. Pmr Spectra of Bicyclo[3.2.0]hept-6-en-2-ones

Compd	Vinyls	Bridgeheads	Other	Methyls	Coupling Constant
<u>29</u>[a]	3.75	6.43	7.30 (1H)	—	$J_{6,7} = 2.7$, $J_{5,6} < 0.5$
	3.96	6.97	7.94 (1H)		
			8.20 (2H)		
<u>31</u>[b]	3.75	—	7.40 (1H)	8.85	$J_{6,7} = 2.6$, $J_{5,6} \leq 0.5$
	4.10	6.97	8.2 (2H)		
			7.9 (1H)		
<u>32</u>	4.37	6.67	7.6-8.4 (4H)	8.27	$J_{7,CH_3} = 1.5$
		7.17			

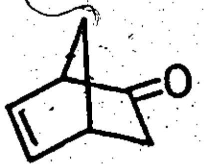
[a] See Figure 39

[b] See Figure 40.

Figure 20. Photoisomerization of Cyclohepta-2,4-dienone



No other products were formed in neutral solvents under these conditions. Specifically, it was demonstrated by glpc analysis that neither of the two possible products shown below were produced. Authentic samples were synthesized and their glpc retention times checked to make certain that they were not eluted simultaneously with 29. In 50% acetic acid, irradiation of 27 yielded the photoproduct 30 in minor amounts (< 1%) after complete photoisomerization of 27. Compound 30 was identified by comparing its glpc retention time to that of authentic material prepared by another route. The small amounts of 30 produced precluded isolation and spectroscopic identification. In 50% acetic acid both 29 and 30 were photostable under conditions which permitted complete isomerization of 27. In all these experiments, essentially all material could be recovered (> 97%). Pmr, ir, and glpc analyses showed no other products.



(b) In FSO_3H

Cyclohepta-2,4-dienone readily dissolved in FSO_3H at -78° to form solutions whose pmr and uv spectra were fully consistent with the O-protonated ketone 27H, Tables 13 and 14. The pmr spectrum was assigned with the aid of decoupling experiments. These are described in a later section of the thesis, Figures 31 and 32.

TABLE 13. UV Spectra of Cyclohepta-2,4-dienones and Protonated Cyclohepta-2,4-dienones[a]

Compd	uv max (nm)	log ε
27	294	3.80
27H	375	3.89
28	300	3.95
28H	398	3.7

[a] at 23°, ketones in methanol, cations in 96% H_2SO_4.

The irradiation of 27H was carried out under the same conditions as those for 6H. After 30-40 minutes all starting cation had photoreacted to give a product whose pmr spectrum at -45° was sufficiently simple to suggest only one product. This spectrum, Table 15, was identical

TABLE 14. Pmr Spectra of Cyclohepta-2,4-dienones and Protonated Cyclohepta-2,4-dienones[a]

Compd	H_2	H_3	H_4	H_5	H_6	H_7	Methyl	Coupling Constant[b]
<u>27</u>	4.01	3.48	3.97	3.53	7.56	7.56	—	$J_{2,3}$ = 11.8, $J_{3,4}$ = 7.4; $J_{4,5}$ = 11.4, $J_{5,6}$ = 5.6
<u>27H</u>[c]	3.09	2.02	3.19	2.72	7.18	6.76	—	$J_{2,3}$ = 11.8, $J_{3,4}$ = 7.9, $J_{4,5}$ = 11.0, $J_{5,6}$ = 5.5
<u>28</u>	—	3.56	4.08	3.75	7.72	7.45	8.10	$J_{3,4}$ = 7.5, $J_{4,5}$ = 11.6, $J_{5,6}$ = 5.5
<u>28H</u>	—	2.05	3.27	2.75	7.30	6.73	7.74	$J_{3,4}$ = 8.3, $J_{4,5}$ = 10.2, $J_{5,6}$ = 5.5

---

[a] All spectra were recorded at 100 MHz at + 37°. Assignments were made on the basis of double irradiation experiments. Ketones were run in CCl_4 (TMS), cations in FSO_3H (CH_2Cl_2).

[b] ± 0.3 Hz.

[c] See Figures 31, 32, 33, 34.

TABLE 15. Pmr Spectra of Bicyclo[2.2.1]hept-2-en-7-ones[a]

Compd	H_1	H_2	H_3	H_4	H_5	H_6	Methyl	Coupling Constant[b]
30	7.24	3.50	3.50	7.24	8.10 8.83	8.10 8.83	—	$J_{2,3}$ = 5.8, $J_{3,4}$ = 3.5, $J_{2,4}$ = 1.8
30H[c]	6.38	3.17	3.17	6.38	7.7 8.3	7.7 8.3	—	$J_{2,3}$ = 5.5
33[d]	—	3.70	3.50	7.27	7.97 8.77	7.97 8.77	8.80	$J_{2,3}$ = 6.0, $J_{3,4}$ = 3.3
33H[c]	—	3.40	3.13	6.37	8.2 8.4	8.2 8.4	8.57	$J_{2,3}$ = 6.0, $J_{3,4}$ = 3.0
9	—	3.62	3.62	7.60	—	8.9	8.83,8.93,9.10	$J_{2,3}$ = 3.5
9H[d,e]	—	3.30	3.30	6.71	—	8.14 8.39	8.60,8.83,8.94	$J_{2,3}$ = 2.7, $J_{6,6'}$ = 12.2

---

[a] All ketones in CCl_4 (TMS)

[b] ± 0.5 Hz

[c] FSO_3H, -45°, 60 MHz

[d] 100 MHz

[e] $SO_2ClF:FSO_3H$, -60°

in all respects to that obtained for authentic* bicyclo[2.2.1]hept-2-en-7-one, 30H in FSO$_3$H, and agreed very well with that reported by Richey for 30H.[83] No other product could be detected in the pmr spectrum of the photoproduct and by using CH$_2$Cl$_2$ as internal standard, little or no material loss was observed. In these determinations any product, < 5% would have remained unnoticed. Quenching this acid solution gave an oil whose ir spectrum matched that of authentic* 30 and glpc analysis showed no other product (2% limit).

In FSO$_3$H 30H was stable to about -20° at which temperature a disappearance (t 1/2 *ca.* 10 min.) of the pmr signals was observed. Irradiation of 30H for 20 minutes at < -60° caused no reaction.

(3) THE PHOTOISOMERIZATION OF 2-METHYLCYCLOHEPTA-2,4-DIENONE

To make absolutely certain that the C$_2$methyl was not involved in the formation of 11 or 11H from eucarvone, 2-methylcyclohepta-2,4-dienone, 28, (Tables 13 and 14), was prepared and its photoisomerizations investigated. All

---

* Prepared by an alternate route by Drs. F. Clark and S. Korn, McMaster University (see experimental section).

irradiations were carried out as in the experiments on <u>27</u> and <u>6</u>. To avoid descriptive repetition of details, the results are summarized in Figure 21 and Table 16. Identification of all products was based on analytical and spectroscopic data obtained for pure samples of <u>31</u>, <u>32</u>, and <u>33</u>. A full description of this data is carried out in the experimental section where the ir and mass spectra and elemental analyses are recorded. In addition, it was shown that <u>31</u> was photochemically converted to <u>32</u> as in the case of <u>7</u> – <u>8</u>. Since the reaction of <u>31</u> to <u>32</u> occurred at 350 nm under the conditions which resulted in reaction of <u>28</u>, it is likely that <u>31</u> is the primary photoproduct of 2-methylcyclohepta-2,4-dienone.

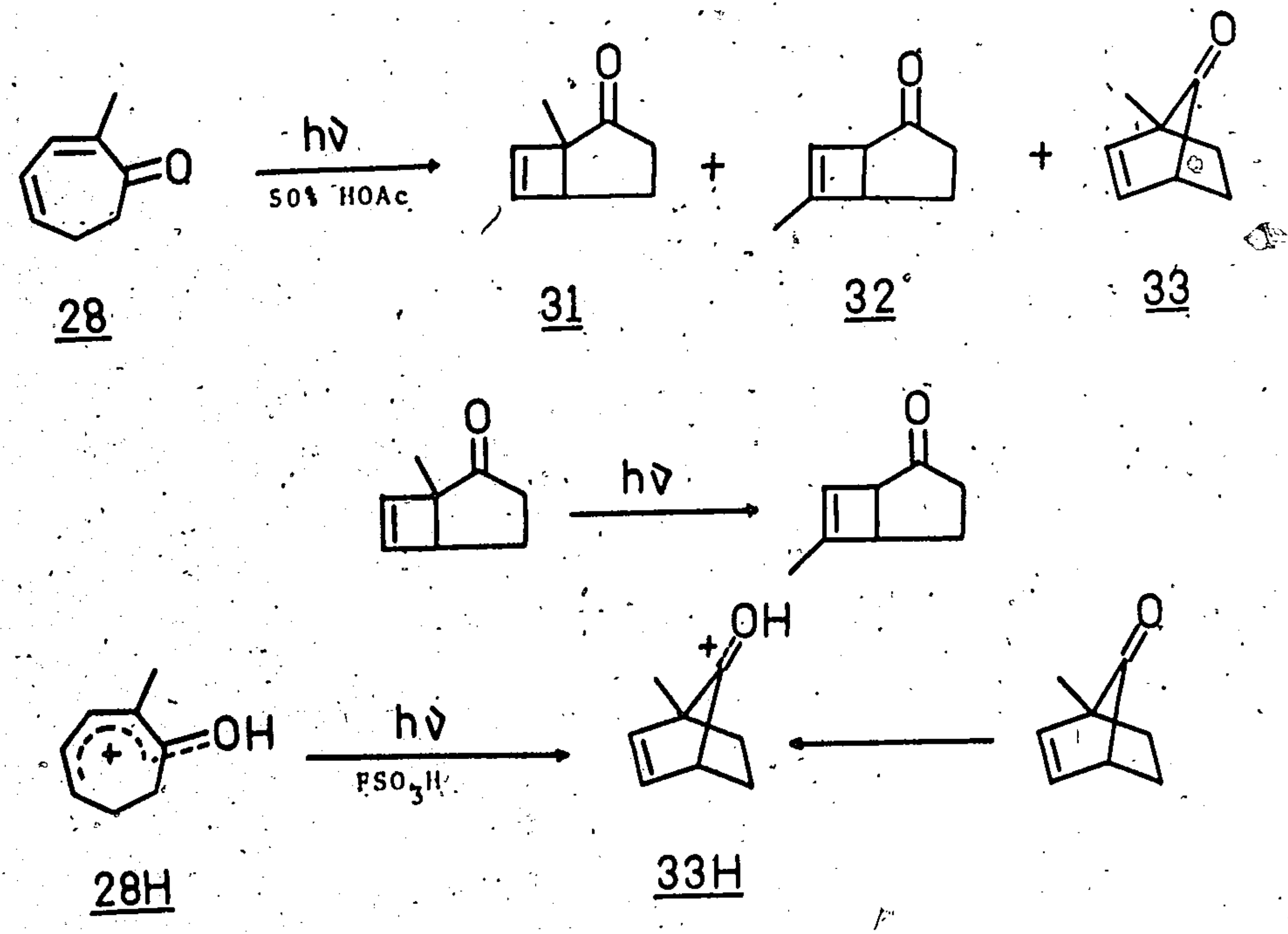
TABLE 16. Product Distribution from the Photoisomerization of <u>28</u>[a]

Solv	% Conversion of <u>28</u>	Relative % of Products <u>31</u> + <u>32</u>	<u>33</u>
Ether	1	100	n.d.
Methanol	20	100	n.d.
50% Aqueous Acetic Acid	80	86	14

[a] at 350 nm, in a merry-go-round apparatus.

The identity of <u>33H</u> produced from <u>28H</u> was based on

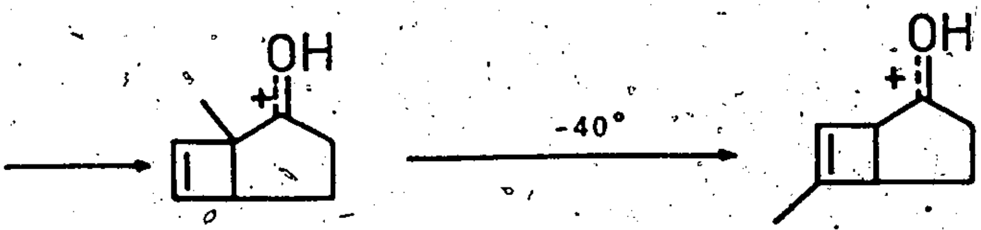
Figure 21. Photoisomerization of 2-Methylcyclohepta-2,4-dienone



the comparison of its pmr spectrum in FSO_3H with that obtained upon protonation of 33 isolated from the neutral ketone irradiations. In addition the pmr of photochemically produced 33H was very similar to those of the corresponding bicyclo[2.2.1]heptenones 9H and 30H (Table 15).

Compound 31 could be protonated in $SO_2ClF:FSO_3H$ at -110° to give a solution whose pmr spectrum was consistent with 31H. At higher temperatures this cation rearranged quantitatively to a new species which on the basis of its spectrum was 32H. This is completely analogous to the isomerization of 7H to 8H described earlier in the thesis. Cation 32H was stable at - 30° for 2 hours.

31



31H

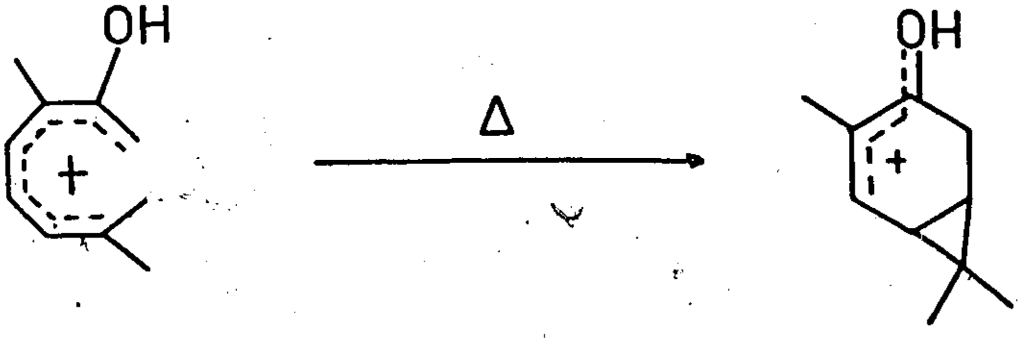
32H

(4) DISCUSSION

It is clear from these results that irradiation of 27 and 28 or their protonated analogues does not result in the formation of bicyclo[4.1.0]heptenone products corresponding to 11 or 11H. Since these experiments were performed under identical conditions as those for eucarvone, there can be little doubt that the gem-dimethyl system at C_6 is a necessary structural feature for this reaction. The results of this study have provided strong evidence for the view that intermediates leading to 11 and 11H from eucarvone have substantial positive charge development at C_6. It is intended to show that the most reasonable structure for these intermediates are 24 and 25 respectively.

Both the substituent effects and the solvent effects (for 6) point to the conclusion that the formation of 11 and 11H does not occur in a concerted fashion. One would not have expected the lack of C_6 methyl groups to completely preclude the formation of bicyclo[4.1.0]heptenones. Nevertheless, to prove this unequivocally, one would have to synthesize a cyclohepta-2,4-dienone with an asymmetric centre at C_6 of known stereochemistry and examine its behaviour upon irradiation. As shown in Figure 19 the concerted reaction would be expected to produce only one stereoisomer. Although two general synthetic routes into this system have been developed,[63,79] considerably more effort would undoubtedly be required for this project.

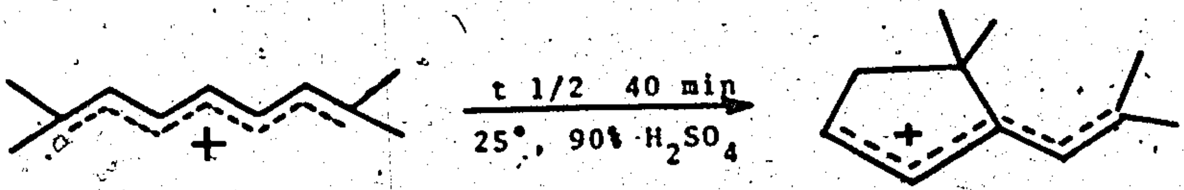
The formation of open chain intermediates such as 23 and 26 in the photochemistry of eucarvone is an interesting proposal although the results do not seem to necessitate their intervention. However, if formed, they must cyclize,



26

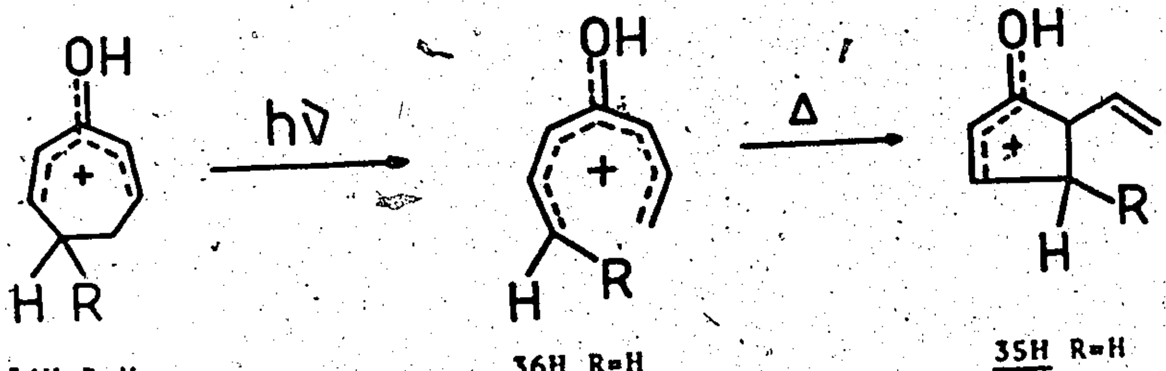
11H

ultimately, to a bicyclo[4.1.0] product according to the mechanisms which have been advanced, Figures 18 and 19. This mode of cyclization is in marked contrast to that established for heptatrienyl cations.[84] Sorensen has shown that in all cases studied these ions thermally isomerized exclusively to cyclopentenyl cations. Apparently, the light in the laboratory accelerated these reactions.[84b]



Recent interest in the question of open chain intermediates in related systems has provided evidence to show that hydroxy heptatrienyl cations cyclize in a corresponding manner. Figure 22 illustrates the results obtained by Noyori for the photoisomerization of protonated cyclohepta-2,6-dienone, 34H, to the protonated vinyl cyclopentenone 35H.[85] The suggested mode of formation of this product involved a photochemical rupture of the C_4-C_5 bond in 34H to give the open chain species 36H which then thermally closed. The possibility that this reaction could be mechanistically interpreted as a concerted [1,3] sigmatropic shift in a non-planar excited state was reasonably discounted on the basis that only one product was obtained in the case where $R=CH_3$.

Figure 22. Photoisomerization of Cyclohepta-2,6-dienone[85]



34H R=H

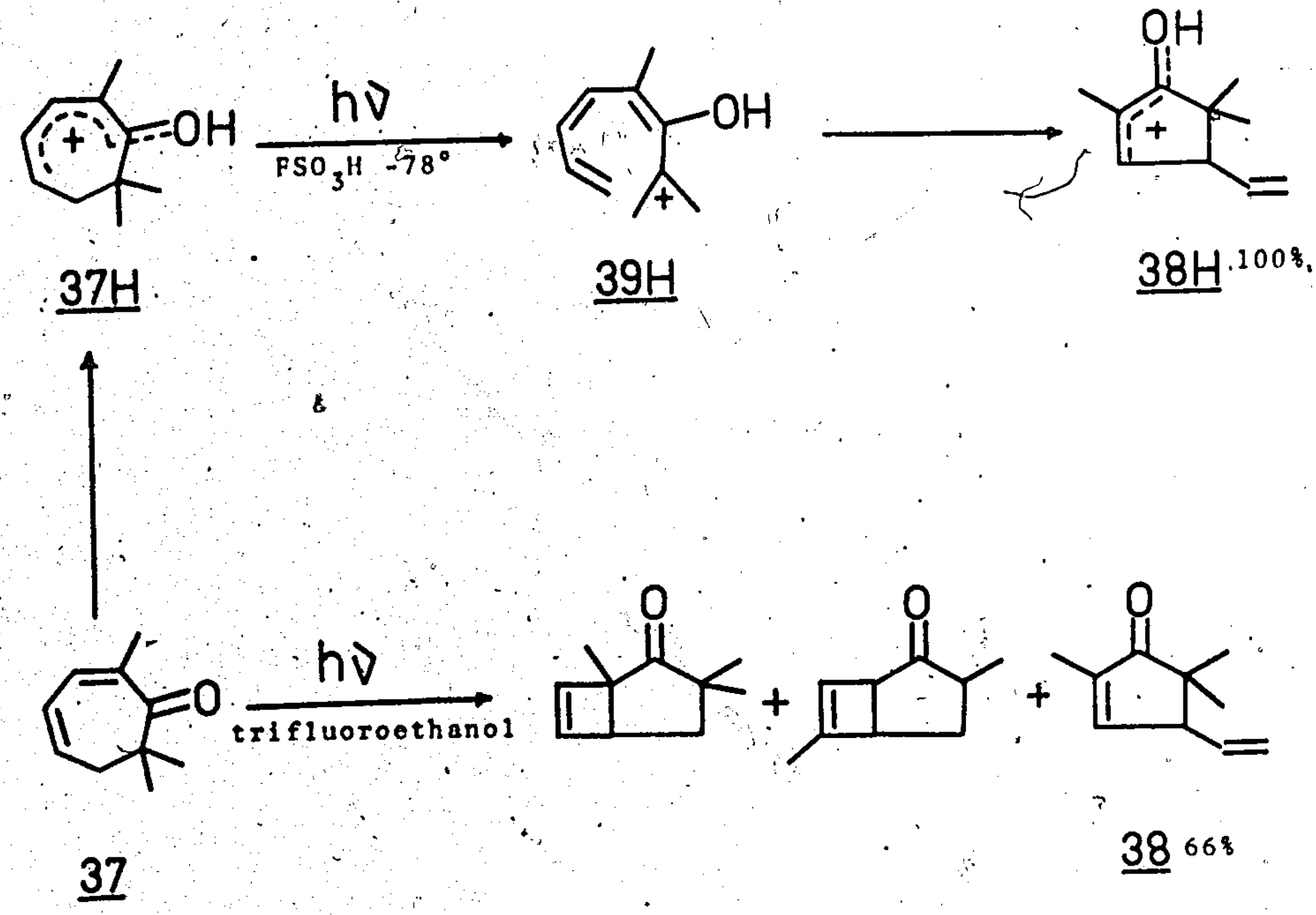
36H R=H

35H R=H

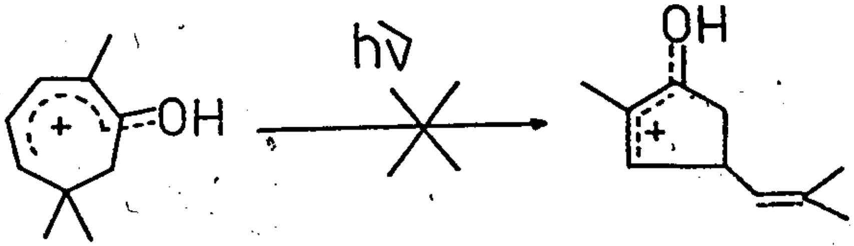
In a related study, Hart reported that the irradiation of protonated 2,7,7-trimethylcyclohepta-2,4-dienone 37H in FSO_3H at -78° produced exclusively the protonated vinyl cyclopentenone 38H.[86] The open chain species 39H was suggested as a plausible intermediate which could cyclize to the observed product, Figure 23. Hart neglected to mention the possibility of a concerted [1,3] sigmatropic shift. However, an examination of a molecular model reveals that if such a reaction occurs, it must take place from an excited state which is considerably distorted. One very interesting aspect of Hart's study was that he obtained 66% of the corresponding ketone 38 via the irradiation of the ketone 37 in trifluoroethanol. Since polar solvents apparently favoured the formation of 38 it was believed to arise from a (π,π^*) state of 37. This work again suggests the very close relationship between the (π,π^*) photochemistry of cyclohepta-2,4-dienones and that of the corresponding protonated dienones.

If we extrapolate the work of Sorensen, Noyori, and Hart to the eucarvone case, then an open chain intermediate such as 26 should have cyclized to the protonated vinyl cyclopentenone as shown below. No product of this type was detected in the irradiations of 6H and considering Hart's work it is reasonable to assume that such a product would have been sufficiently stable to be isolated and

Figure 23. Photoisomerization of 2,7,7-trimethylcyclohepta-2,4-dienone[86]



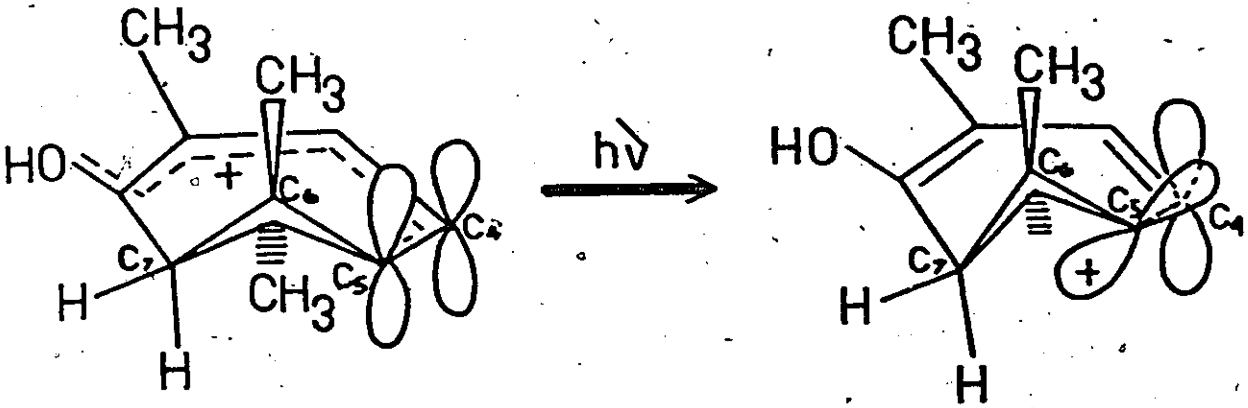
characterized. For these reasons, it is felt that the formation of <u>11H</u> from <u>6H</u> involves only the intermediate <u>25</u>.



The direct formation of <u>25</u> takes place essentially via a 1,2-alkyl shift of C_7 to C_5. Since protonated eucarvone is thermally stable under the irradiation conditions, this reaction must occur in the (π,π^*) excited state. Mechanistically this reaction can be viewed as follows.

Excitation to the (π,π^*) singlet results in some degree of positive charge localization on C_5 of the protonated dienone system.[3b,27b] A subsequent, or perhaps concurrent, twisting about the C_4-C_5 bond would permit a favourable interaction between the electrons in the C_6-C_7 sigma bond with the electron deficient orbital on C_5. Bonding between C_7 and C_5 would localize the charge upon the carbon atom bearing the methyl groups.

There is certainly abundant evidence to indicate that twisting occurs in excited states of medium ring unsaturated ketones. Excellent chemical and spectroscopic



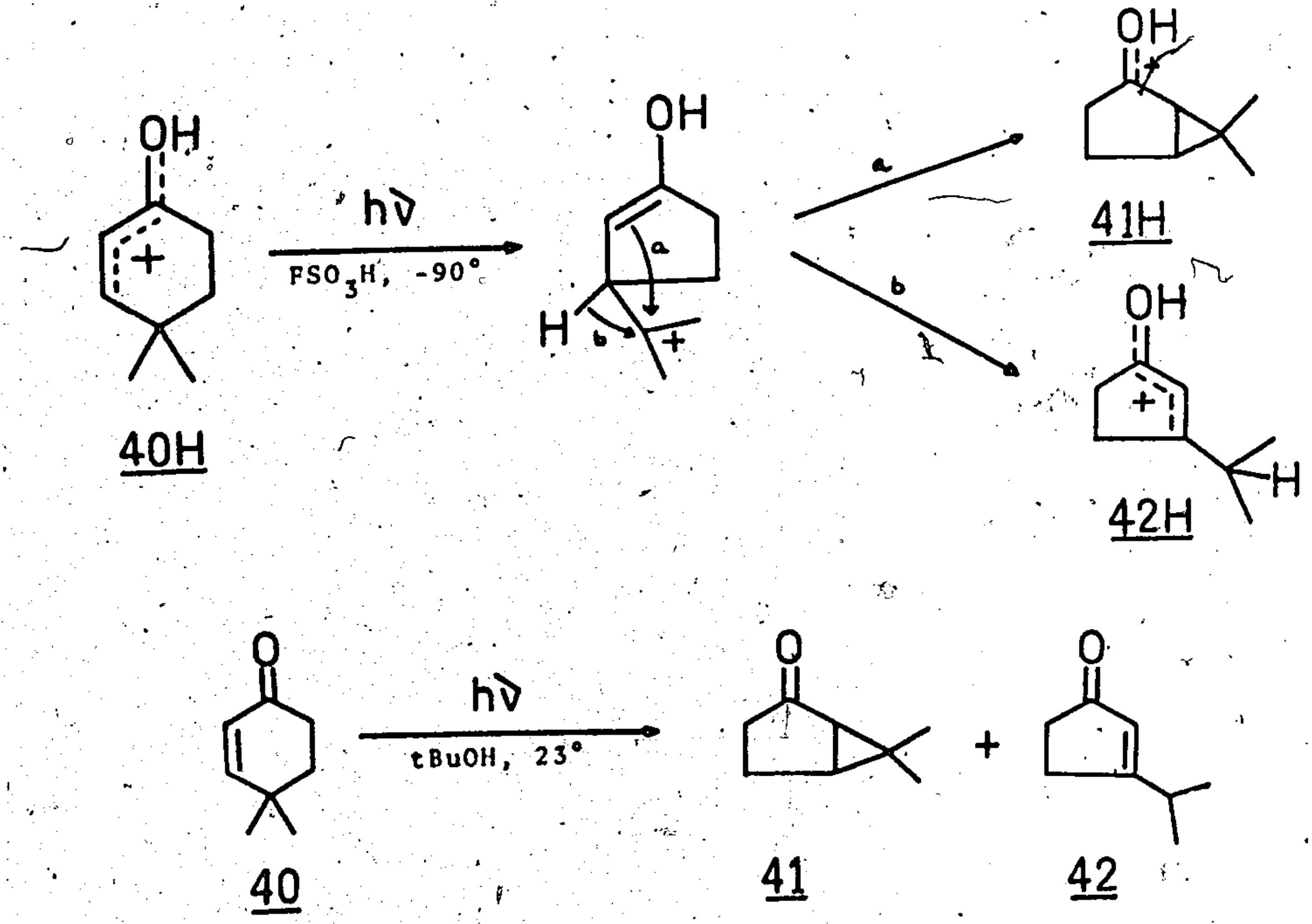
6H

6H*

observations demonstrate that trans-enones are the primary irradiation products of cyclooct-2-enone and cyclohept-2-enone.[87] Calculations by Devaquet upon acrolein suggest that twisting around the ethyleneic double bond results in stabilization of both singlet and triplet (π,π*) states.[88] Very recently Childs has provided conclusive evidence to show that double bond rotation takes place upon irradiation of a cationic system.[89] Photolysis of protonated trans-crotonic acid in 96% H_2SO_4 resulted in a cis-trans isomerization to give a photoequilibrium consisting of 42% cis and 58% trans.

Some precedent for a similar type of 1,2-alkyl shift in a related system can be found in very recent work by Childs and coworkers.[90] It was observed that protonated 4,4-dimethylcyclohexenone, 40H, was photoisomerized to a

Figure 24: Photoisomerization of 4,4-dimethylcyclohexenone[90]



mixture of protonated 6,6-dimethylbicyclo[3.1.0]hexan-2-one, 41H, and protonated 3-isopropylcyclopentenone, 42H, Figure 24. These results are formally analogous to the formation of 11H and 13H from 6H, the important difference being that 40H must give the intermediate directly. No open chain species can be involved in this case. Interestingly enough, under similar conditions protonated cyclohexenone and 4-methylcyclohexenone did not undergo any isomerization. The effect of the two methyl groups no doubt is to stabilize a positive charge developed upon C_4.

The photoisomerization of the neutral ketone 40, studied by Chapman,[91] is also shown in Figure 24. The parallel between these two reactions is striking, especially since rearrangements of simple enones such as 40 most likely take place from $(\pi,\pi^*)^3$ states.[6,8]

Returning to the formation of 25, it is felt that demotion of the excited state to the ground state takes place after formation of the $C_5 - C_7$ bond and localization of the charge on C_6. The subsequent reactions of 25 are typical cationic processes. The predominance of 11H over 13H is possibly the result of a faster rate of $C_6 - C_4$ bond formation verses a 1,2-hydride shift (Figure 19). No definite reason for this can be stated at this time, although it is worthwhile to note that the rate of a 1,2-hydride shift to give 13H would be dependent upon the dihedral angle between the electrons in the migrating bond and the positive lobe on the adjacent carbon atom.[92]

In the absence of the gem-dimethyls at C_6 twisting about the $C_4 - C_5$ bond may be an important process in the (π,π^*) excited states of 27H and 28H. However, $C_5 - C_7$ bonding would be a relatively high energy route compared to the alternate, and ostensibly equally favourable $C_5 - C_1$ bond formation. This latter process is discussed in the next section concerning the formation of the bicyclo[2.2.1]heptenones.

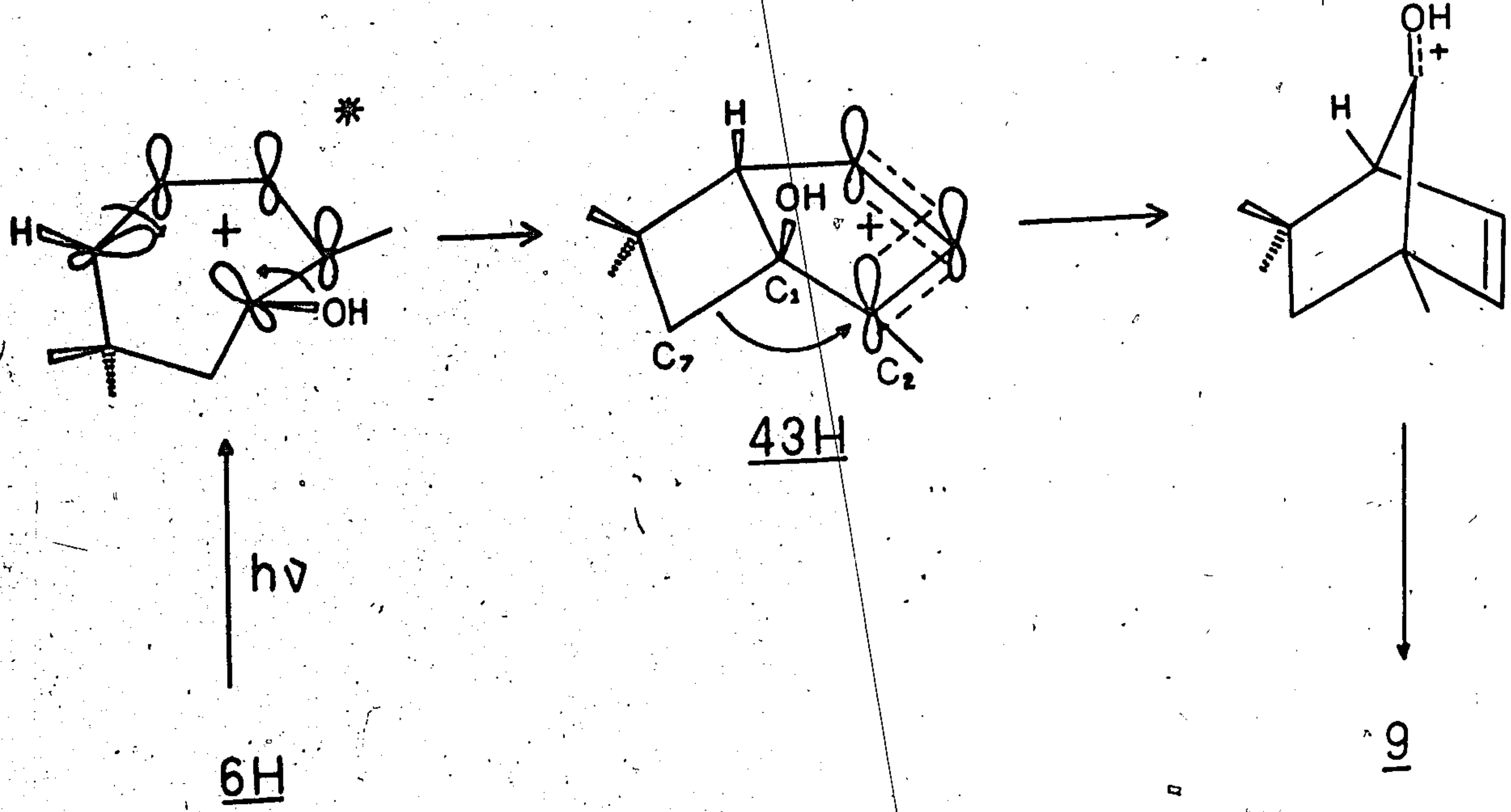
The lack of any bicyclo[4.1.0]hept-2-en-4-ones from the neutral ketones 27 and 28 suggests that the C_6 methyl groups are essential for this type of reaction. Intermediates involved in the formation of 11 from 6 must be characterized by an electron deficient C_6. It is felt that the most reasonable representation for this species, according to the arguments above, is the structure 24. The very modest amounts of carvacrol ($< 1\%$) formed from 6 in methanol may be a result of the zwitterionic nature of 24. One would expect that the dienolate moiety of this intermediate, being more nucleophilic than the dienol part of 25, may compete more favourably for the electrophilic centre on C_6 than the electrons of the C - H sigma bond in the 1,2-hydride-shift process.

(5) A DISCUSSION OF THE MECHANISM INVOLVED IN THE FORMATION OF BICYCLO[2.2.1]HEPTENONES FROM CYCLOHEPTA-2,4-DIENONES

There are a number of reasons for including this section. Although only minor amounts of these products are obtained from eucarvone, they are the exclusive products of 27H and 28H, the less substituted cyclohepta-2,4-dienones. The results of the previous sections have provided some evidence for the mechanism of these reactions which should be discussed.

The most probable mechanism for the formation of bicyclo[2.2.1]heptenones from protonated cyclohepta-2,4-dienones must involve a photochemically allowed disrotatory closure in the excited state of the cation to give an intermediate, represented generally as 43H, Figure 25. Similar photochemical closures have been postulated as initial steps in the photorearrangements of tropylium cations,[62] protonated cyclohexadienones[35c] and other systems,[93] and ample supporting proof is available at this time. The intermediate 43H can then be considered to undergo a thermal 1,2-alkyl shift of C_7 to C_2. Such a step has ample precedent in the work reported by Winstein and Brookhart[71] which was discussed earlier in this thesis,

Figure 25. The Formation of Bicyclo[2.2.1]hept-2-en-7-ones from Protonated Cyclohepta-2,4-dienones



(Part 2 - iib). In the case of 43H, there will exist a strong driving force to place the positive charge upon the carbon bearing the hydroxy group.

In addition to the reaction in strong acid, there is considerable evidence to support the view that intermediates analogous, or perhaps identical, to 43H are formed in the formation of bicyclo[2.2.1]heptenones from the neutral cyclohepta-2,4-dienones. It will be recalled that in buffered methanol an additional photoproduct of eucarvone was obtained and identified as 17. The obvious relationship of 17 to 9 led to the proposal that there existed a common intermediate for these products. It is the conviction of this author that this intermediate is best represented as 44H. The formation of 44H could occur (as in the case for 43H) via a photochemical closure of a protonated (π,π^*) state of 6. In weakly acidic solvents, nucleophilic capture at C_4 could compete with the 1,2-alkyl shift to produce 17, Figure 26.

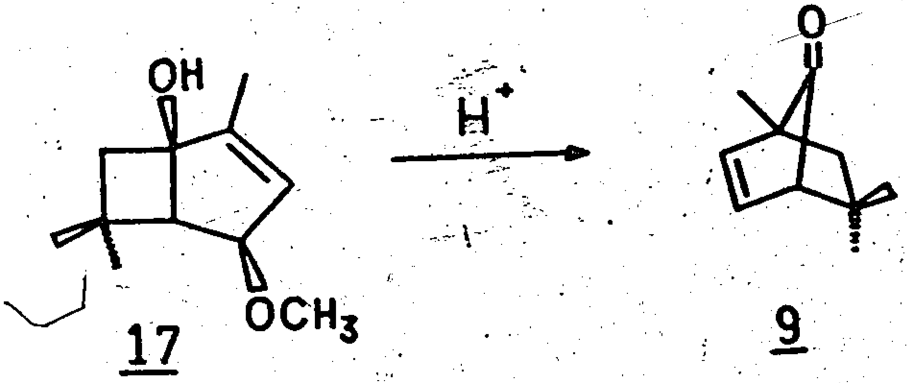
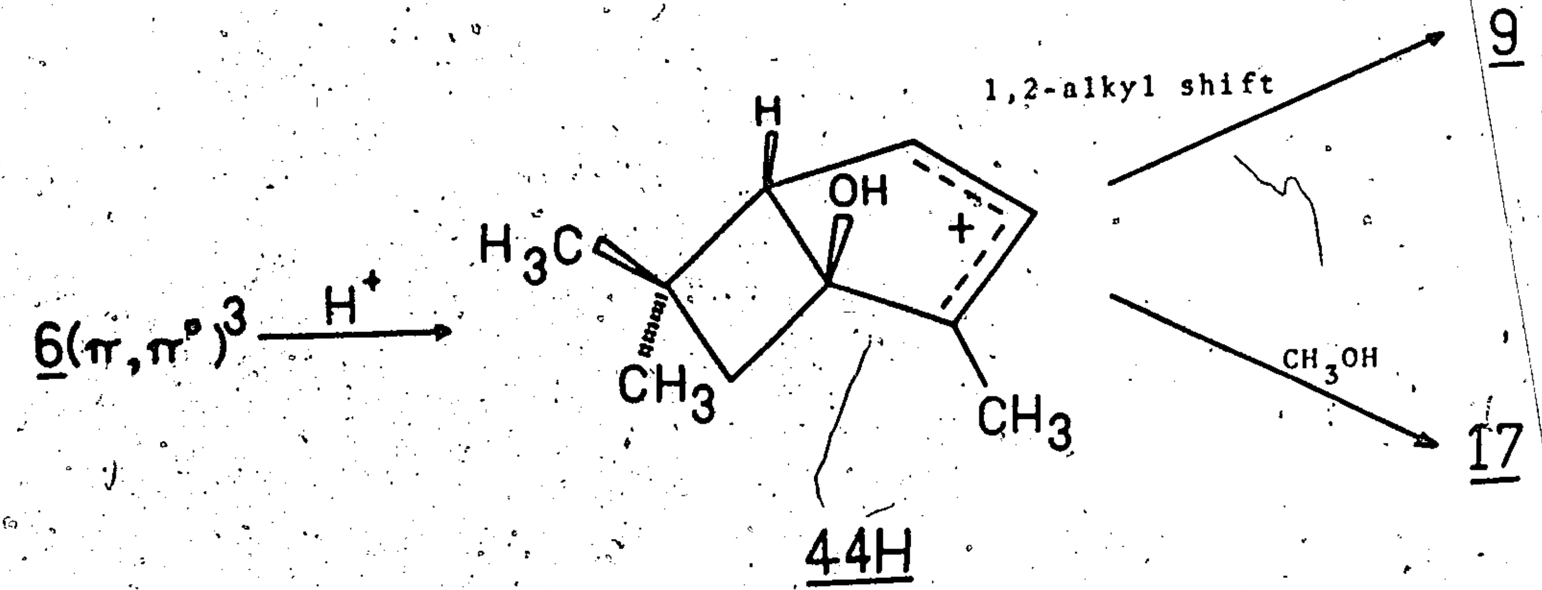


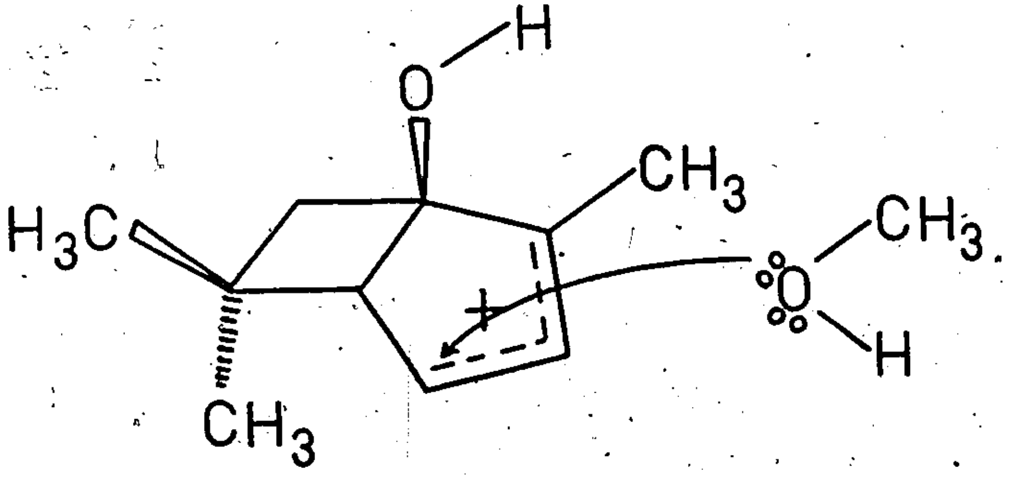
Figure 26. The Formation of 9 and 17 from Eucarvone



Nucleophilic trapping of intermediates involved in photochemical isomerizations of unsaturated ketones have been reported quite frequently in the chemical literature.[49bc,92,94] Almost without exception these authors have offered the formation of the thus formed adducts as proof for the formation of ionic intermediates. For the eucarvone example, the additional observation that protonated eucarvone yields <u>9H</u> most certainly implicates ionic intermediates in the formation of 1,5,5-trimethylbicyclo[2.2.1]-hept-2-en-7-one. The comparison between the ketone and protonated ketone is again striking and suggests the operation of a similar mechanism. Undoubtedly, further studies will indicate that the formation of <u>30</u> and <u>33</u> from <u>27</u> and <u>28</u> involves analogous mechanisms.

The stereochemistry of the methoxy group in <u>17</u> has been assigned as <u>syn</u> to the hydroxy group on the basis of coupling constant arguments. No other adduct was obtained to suggest that capture at C_2 occurred as well in these reactions, although any product $\leq 0.5\%$ was not further investigated. Examination of a molecular model of <u>17</u> reveals that the approach of methanol to the "topside" of the cation is sterically more favourable than attack from the "underside" where the C_7 methyl group provides considerable steric hinderance. In line with this thought, it is perhaps not surprising that no product was detected which resulted from capture at C_2. Steric congestion resulting from the close proximity of the hydroxy group may play a part, (Figure 27).

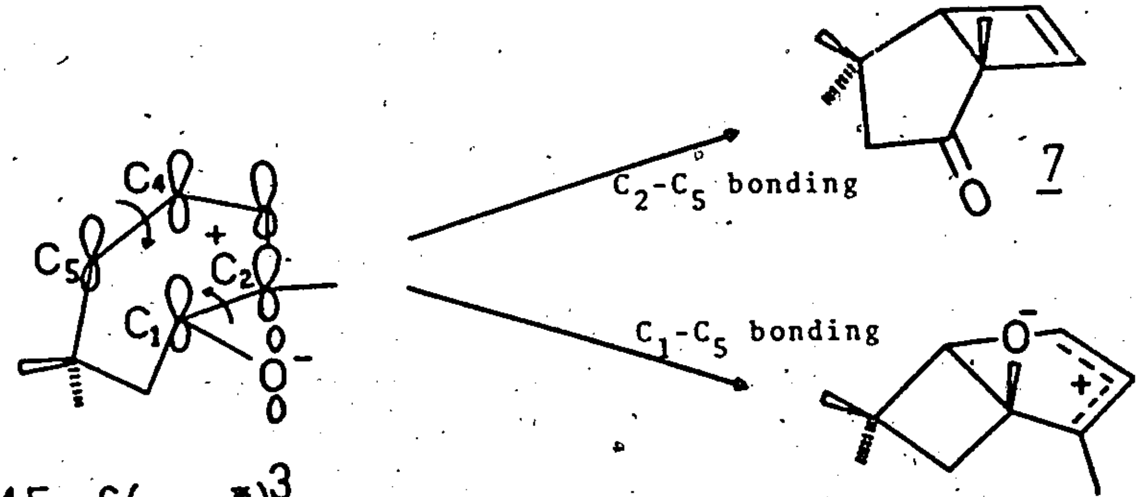
Figure 27. Steric Effects in the Formation of 17.



44H

Before terminating this discussion, it is of interest to consider why protonation is a necessary step in the production of 9 and 17. If we accept the fact that photochemical closure is the initial process which occurs in this reaction, then C_1-C_5 bonding in a zwitterionic species such as 45 will localize charge upon oxygen and the allyl system. This charge separation would be expected to be a relatively high energy route with respect to alternative processes such as C_2-C_5 bonding which would form 7. The molecular motions involved in bonding between C_5 and C_1 or

C_2 are closely related and it will be recalled that 9 and 17 were produced at the expense of 7. It is felt that unless prior protonation of the excited state occurs, then the energy barrier to closure would be too high for C_1-C_5 bonding and would favour the alternate C_2-C_5 process.

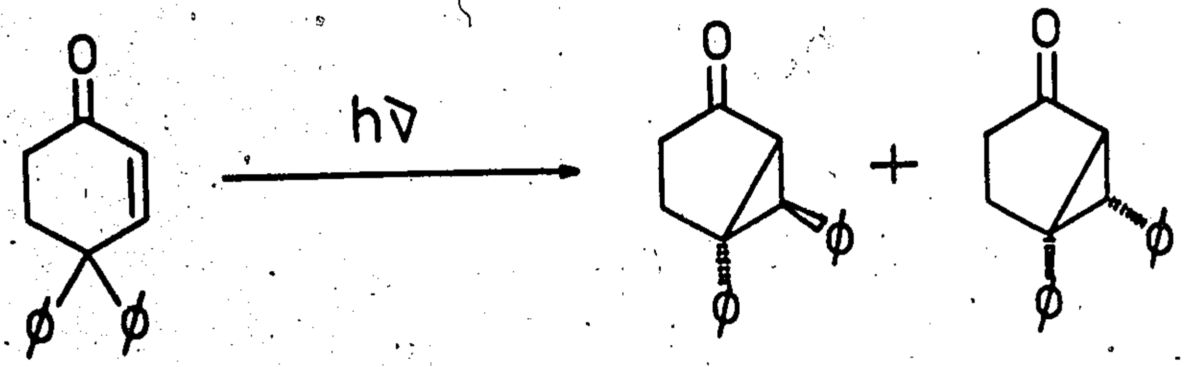


7

45 $6(\pi,\pi^*)^3$

Energy barriers in the reactions of excited states have been demonstrated in recent work published by Zimmerman.[95] The quantum yield for the photochemical rearrangement of 4,4-diphenylcyclohexenone 46 to cis-and trans-5,6-diphenylbicyclo[3.1.0]hexan-2-one was shown to increase with reaction temperature. For example, a 50° rise in temperature enhanced the quantum yield of phenyl migration by sixfold. Independent experiments showed that this was not due to changes in solvent viscosity as the quantum yield at 20° in hexane was the same as in the fivefold more viscous n-dodecane. By determining

Photochemical Rearrangement of 4,4-diphenylcyclohexenone^{95}



46

Stern-Volmer plots at different temperatures he was able to obtain the changes in rates of triplet reaction, k_r, and decay, k_d, with temperature. The results, reproduced below in Table 17, show a sixteenfold acceleration for k_r and a twofold increase for k_d. This corresponds to an activation energy of 10.5 kcal/mole for the reaction of the triplet state.

TABLE 17. Temperature Dependence of Excited State Reaction Rates[96]

Temp (°C)	k_r (sec^{-1})	k_d (sec^{-1})
20	7.1×10^{6}	2.7×10^{8}
73	1.22×10^{8}	5.7×10^{8}

The difference in relative amount of bicyclo[2.2.1]hept-2-en-7-ones produced from <u>27</u> and <u>28</u> in 50% aqueous acetic acid can also be rationalized in terms of an excited state energy barrier to reaction. During the C_5 - C_1 bonding process, positive charge is localized on the allyl system consisting of C_2, C_3, and C_4. A methyl substituted system would be expected to accommodate a positive charge more readily than an unsubstituted one.

PART 4. CONCLUSIONS

CONCLUSIONS

1) This study has demonstrated that (π,π^*) excited states, most probably singlets, are definitely involved in the formation of 11 from 6. The bicyclo[3.2.0]hept-6-en-2-one 7 results from an energetically similar $(n,\pi^*)^1$ and from a $(\pi,\pi^*)^3$. In acidic solvents the latter state is protonated and diverted to 9. These conclusions are represented in Figure 28.

2) The formation of 11 and 9 from 6 and 6H involves ionic type intermediates. The most reasonable representations of these species are 24 and 25 for 11 and 44H and 43H for 9.

3) Substituents play an important role in determining the subsequent reactions of (π,π^*) excited states of cyclohepta-2,4-dienones and their protonated analogues (Figure 29).

4) The results of this thesis have demonstrated that a study of the photochemistry of a protonated ketone can provide considerable information concerning the nature of the excited states involved in photoisomerizations of the corresponding ketone. The generality of this approach has begun to emerge from further studies by Childs[90] and Hart[86].

Figure 28. The Photoisomerization of Eucarvone

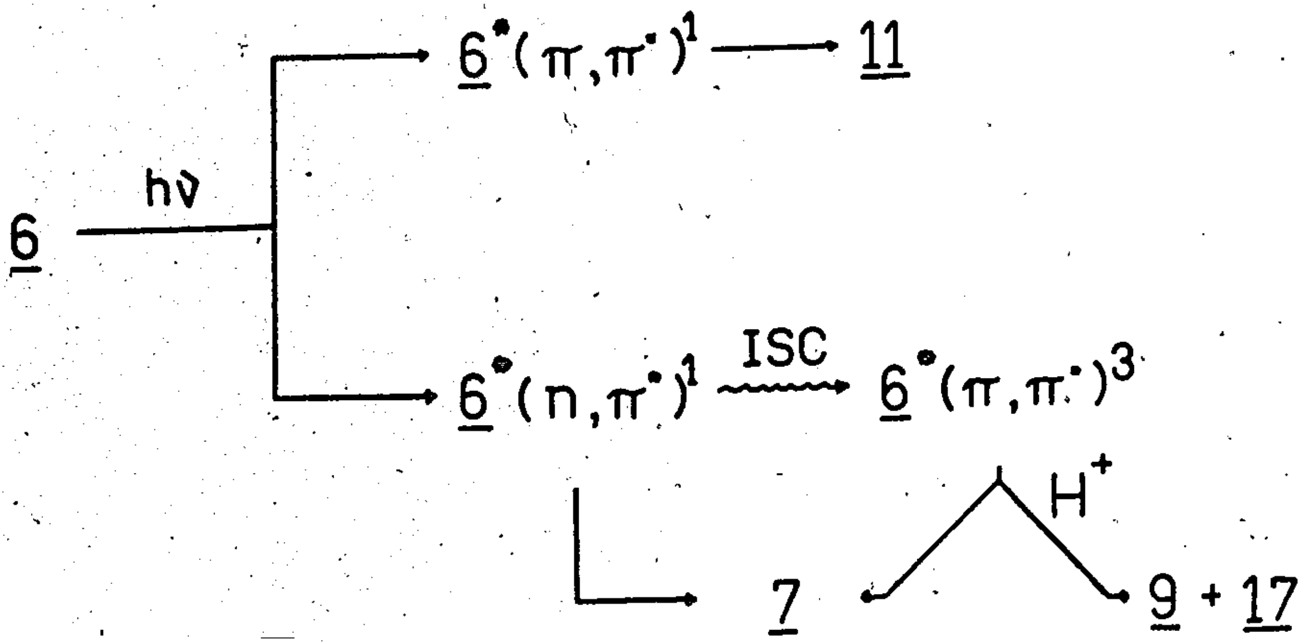
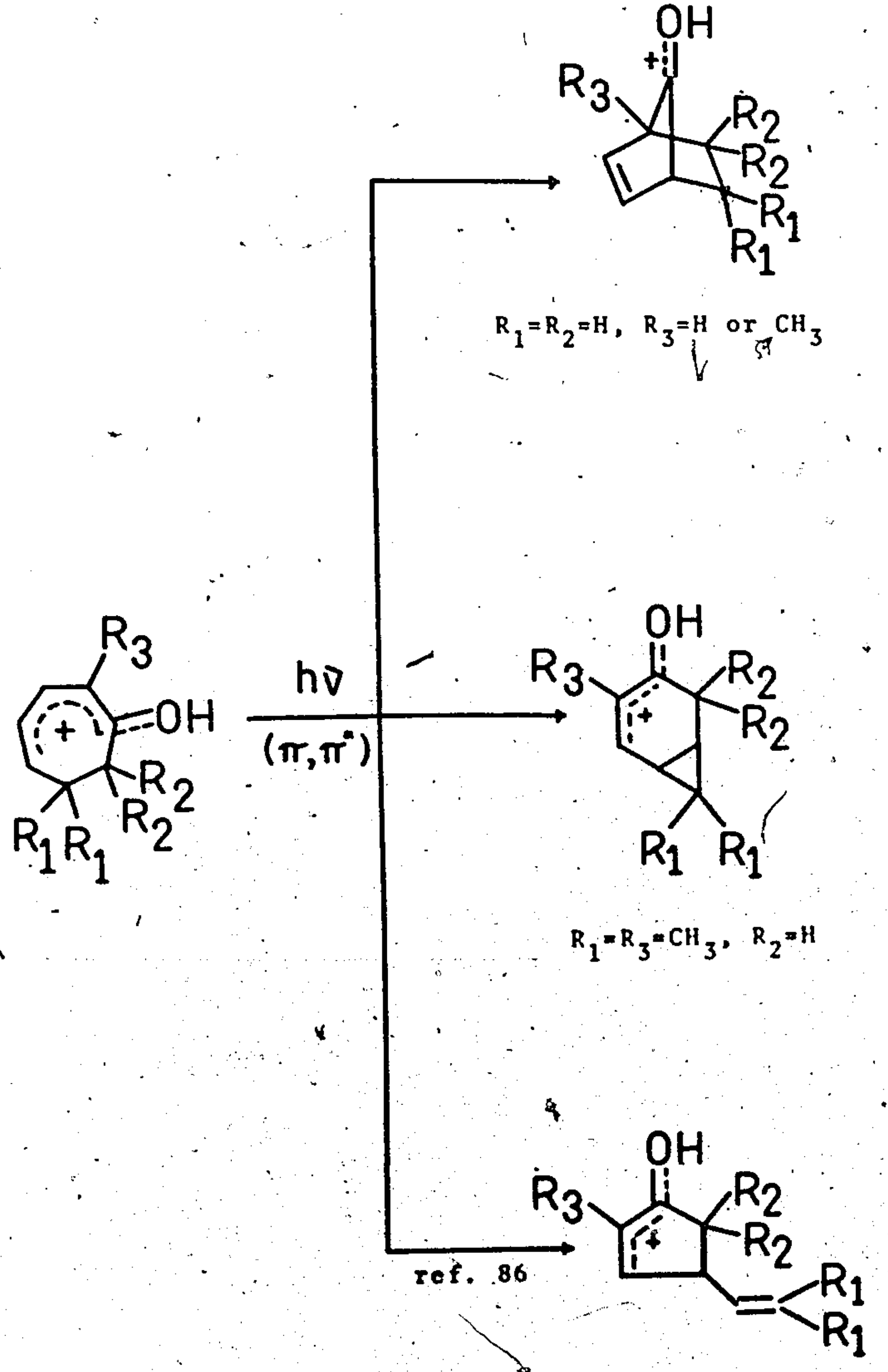


Figure 29. Substituent Effects upon the Photoisomerization of Protonated Cyclohepta-2,4-dienones



$R_1=R_2=H$, $R_3=H$ or CH_3

$R_1=R_3=CH_3$, $R_2=H$

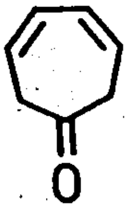
$R_1=H$, $R_2=R_3=CH_3$

PART 5. THE PREPARATION OF CYCLOHEPTA-2,4-DIENONE

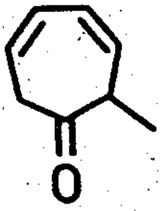
THE PREPARATION OF CYCLOHEPTA-2,4-DIENONE

(1) INTRODUCTION

During the course of the work on eucarvone it became necessary to study the photoisomerizations of cyclohepta-2,4-dienone 27 and its 2-methyl derivative for reasons already pointed out. However, the only reported preparation of 27 did not appear particularly convenient for synthesizing large quantities in a state of high purity.[96] In addition, this method was not suitable for preparing 28. One approach which did seen extremely viable was to isomerize the readily available cyclohepta-3,5-dienones 47 and 48.[97]



47



48

Thermal interconversion of 47 and 27 had been reported to take place in solution above 60°.[98] At 80° an equilibrium was reached which consisted of 35% 47 and 65% 27. Despite the apparent simplicity of this reaction, it was not particularly attractive in terms of a synthetic procedure because the final step required the separation of double bond isomers. Furthermore, as this isomerization was shown to proceed via a 1,5-hydride shift,[97] there was compelling evidence to suggest that 48 would produce 28 and the isomeric 7-methylcyclohepta-2,4-dienone 49 by this route.[99]

It is evident that a thermodynamic equilibrium of the ketones will be reached irrespective of the manner in which isomerization is carried out. A potential solution to this problem might be to structurally modify both 47 and 48 so that isomerization of the modified forms would yield solely the linear conjugated isomers 27 and 28. A clue to the mode of this structural modification was provided in a paper by Hogeveen published in 1968.[100]

In this study, Hogeveen reported the observation that cyclohex-3-en-1-one was very rapidly isomerized to cyclohex-2-en-1-one in HF-SbF$_5$. It thus appeared that non-conjugated unsaturated ketones could be isomerized to the fully conjugated system via thermal reactions of the oxygen protonated forms. One might expect then that the structural change which was required in the case of the cyclohepta-3,5-dienones was protonation of the carbonyl oxygen. With this in mind, a study was made of the thermal reactions of 47 and 48 in FSO_3H.

RESULTS AND DISCUSSION

(2) THE PROTONATION OF CYCLOHEPTA-3,5-DIENONES

Compounds 47 and 48 were readily protonated in fluorosulphuric acid to form solutions whose pmr spectra (Table 18) were completely consistent with the hydroxy cation structures 47H and 48H, respectively. Recovery of the ketones unchanged could be effected by careful, low temperature (-45°) neutralization of the acid solutions, Figure 30,

Figure 30. The Protonation of Cyclohepta-3,5-dienones

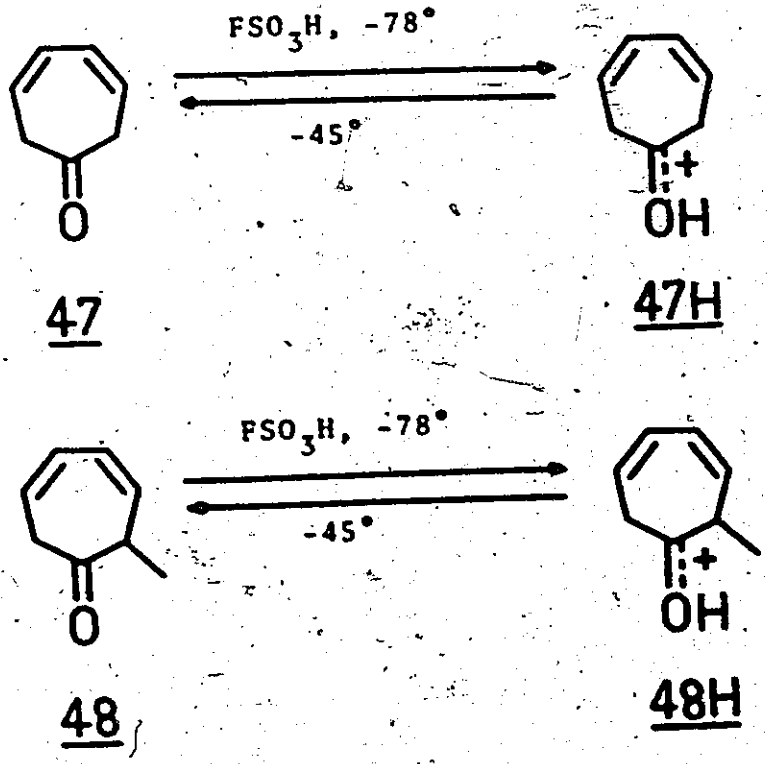


TABLE 18. Pmr Spectra of Cyclohepta-3,5-dienones and Protonated Cyclohepta-3,5-dienones[a]

Compd	H_2	H_3	H_4	H_5	H_6	H_7	Methyl	Coupling Constant[b]
47	6.95	4.14	3.70	3.70	4.14	6.95	—	$J_{2,3} = J_{6,7} = 5.5$, $J_{3,4} = J_{4,5} = 10.0$
47H	6.10	4.25	3.18	3.18	4.25	6.10	—	$J_{2,3} = J_{6,7} = 6.0$, $J_{3,4} = J_{5,6} = 10.0$
48	7.04	4.50	3.77	3.77	4.18	7.0	8.77(J=6.7)	$J_{2,3} = 4.8$, $J_{3,4} = 10.8$, $J_{4,5} = 8.5$, $J_{5,6} = 4.5$
48H	6.37	4.84	3.18	3.18	4.02	6.0	8.34(J=6.9)	$J_{3,4} = J_{5,6} = 10.3$, $J_{4,5} = 8.3$; $J_{6,7} = 5.5$

[a] All spectra at 100 MHz, ketones in CCl_4 (TMS) at +37°, cations in FSO_3H (CH_2Cl_2) at -30°. Assignments made by decoupling experiments.

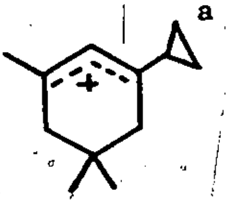
[b] ± 0.3 Hz.

Examination of the pmr spectrum of 47H revealed that the C_2 and C_7 protons had moved to lower field by 0.85 ppm. This value agrees very well with the 1.0 ppm shift Olah reported for the α-protons of cycloheptanone and cyclohexanone upon protonation of the carbonyl oxygen.[101a] In addition, the protons on C_4 and C_5 were found to be substantially deshielded relative to their position in 47. However, the C_3 and C_6 hydrogens appeared to have experienced an upshield shift. Quite reasonably, if only inductive effects were operative, one would have expected a more pronounced deshielding effect for the protons bonded to C_3 and C_6 than for those on C_4 and C_5.

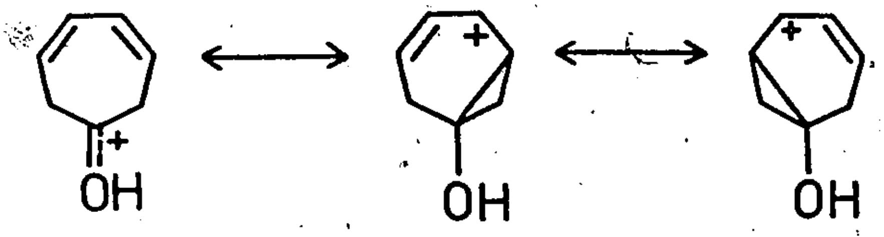
To explain these observations, it is reasonable to propose that there exists an interaction between the electrophilic carbon, C_1, with the relatively electron rich diene fragment. A symmetrical type of interaction between C_1 and C_3 and C_6, while possible, would be energetically unfavourable being a cyclicly delocalized system of 4π electrons.[102] An alternative approach, which can explain the pmr spectrum of 47H, would suggest that this overlap is of an unsymmetrical nature and that the resonance forms 47H a-b contribute significantly to the structure of 47H.

Support for this view can be obtained from the uv spectrum of 47H. As indicated in Table 19, 47H displayed a broad, fairly intense absorption maximum of 318 nm in

TABLE 19. Uv Spectra of Cyclohepta-3,5-dienones and Protonated Cyclohepta-3,5-dienones

Compd	Solv	Temp(°C)	λmax(nm)	logε
<u>47</u>	CH_3OH	25	227	3.62
<u>47H</u>	FSO_3H	-50	318	<u>ca</u>. 3.0-3.3
<u>48</u>	CH_3OH	25	228	3.64
<u>48H</u>	FSO_3H	-50	315	<u>ca</u>. 3.0-3.3
 [a]	H_2SO_4	25	333	4.75

[a] Taken from reference 103.



47H-a 47H-b

FSO$_3$H at -55°. Similarly, 48H was observed to produce a band at 315 nm. Since protonated saturated ketones show no absorption above 220 nm,[104] and since the $\pi-\pi^*$ band of the ketones are at 230 nm, these maxima in FSO$_3$H must be due to a cyclopropyl-allyl type of interaction. The uv spectra of some cyclopropyl-allyl cations have been reported by Deno to contain bands at *ca.* 330 nm.[103] One example is given in Table 19.

(3) THERMAL ISOMERIZATION OF PROTONATED CYCLOHEPTA-3,5-DIENONES

When solutions of 47H were heated to 0°, a clean isomerization took place, $k = 8.5\times10^{-4}$ sec^{-1}, to give a new cation whose pmr spectrum showed the same ratio of olefinic to aliphatic protons. The 100 MHz spectrum of this cation is reproduced in Figures 31 and 32. These are actual Xerox copies of the spectrum. The coupling pattern of the vinyl region of this product ~~has~~ been analyzed in Figure 31 and is completely consistent with that expected for protonated cyclohepta-2,4-dienone, <u>27H</u>. H_3 is the lowest field proton, as in eucarvone, and is coupled to H_2, $J = 11.8$ Hz, and further split by H_4, $J = 7.9$ Hz. The five line multiplet at τ 2.72 is H_5, coupled to H_4, $J = 11.0$, and the two protons on H_6, $J = 5.9$ Hz. The remainder of the vinyl region consisted of a doublet for H_2 at τ 3.09 and H_4 a doublet of doublets at τ 3.19. Figure 32 shows the aliphatic region. This, being exceedingly complicated, was less informative and was not further analyzed. In fact, the assignment was made on the basis of decoupling experiments, shown in Figures 33 and 34. When the multiplet at τ 7.18 was irradiated the five line pattern for H_5 was observed to collapse into a doublet. On the other hand when the lower field multiplet was irradiated, little, or no, change took place in the vinyl region, Figure 34.

Quenching this acid solution yielded an orange oil which was shown by glpc analysis to be contaminated with no other products and only <u>ca</u>. 0.5% <u>47</u>. The ir, uv, and pmr spectra (see experimental and Table 14) were identical to those reported for cyclohepta-2,4-dienone.[96,98,105] They agreed very well with those obtained for <u>27</u> obtained by the author via the thermal isomerization of <u>47</u>.

Figure 31. Analysis of the Vinyl Protons of 27H

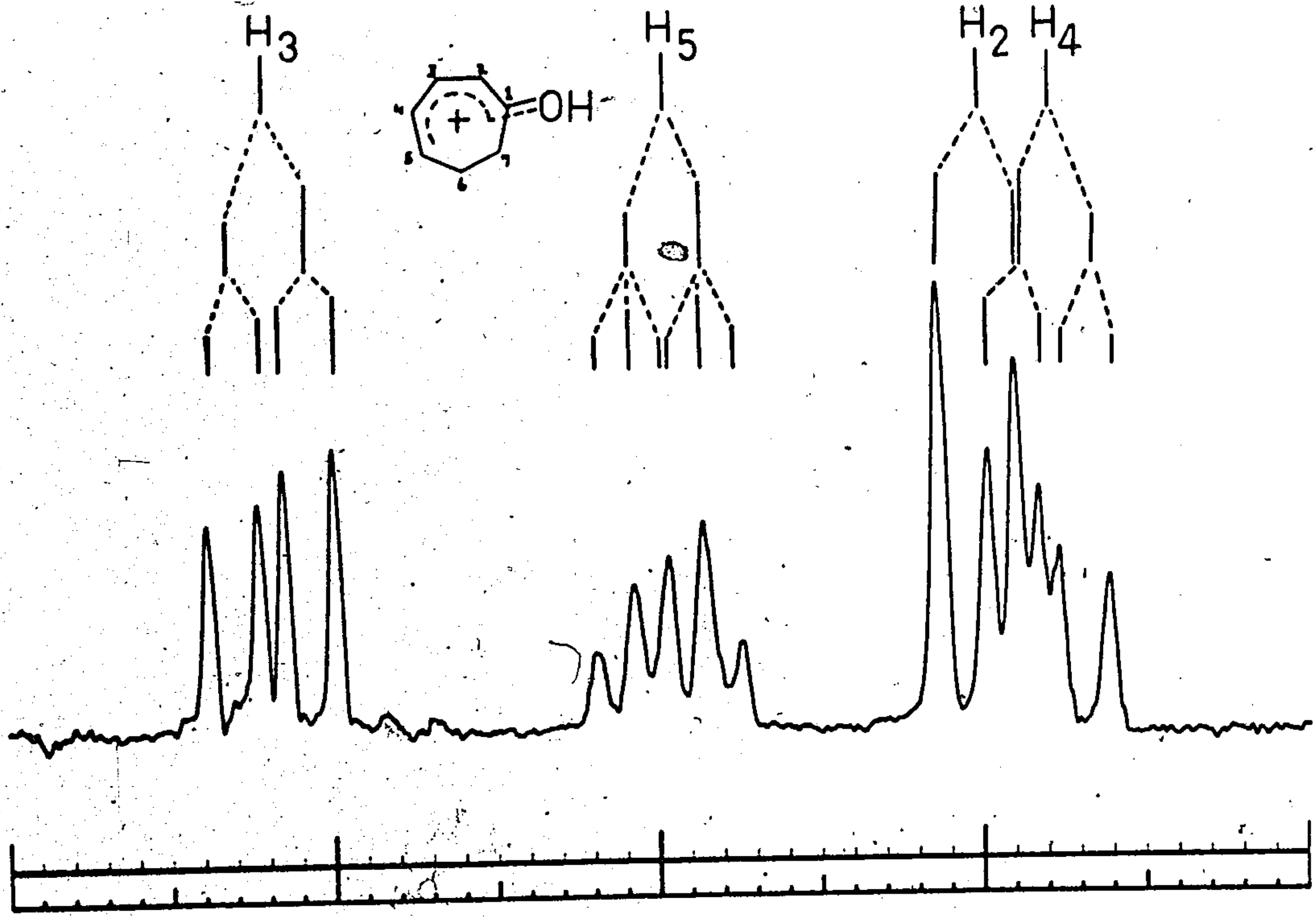


Figure 32. The High Field Region of the Pmr Spectrum of 27H

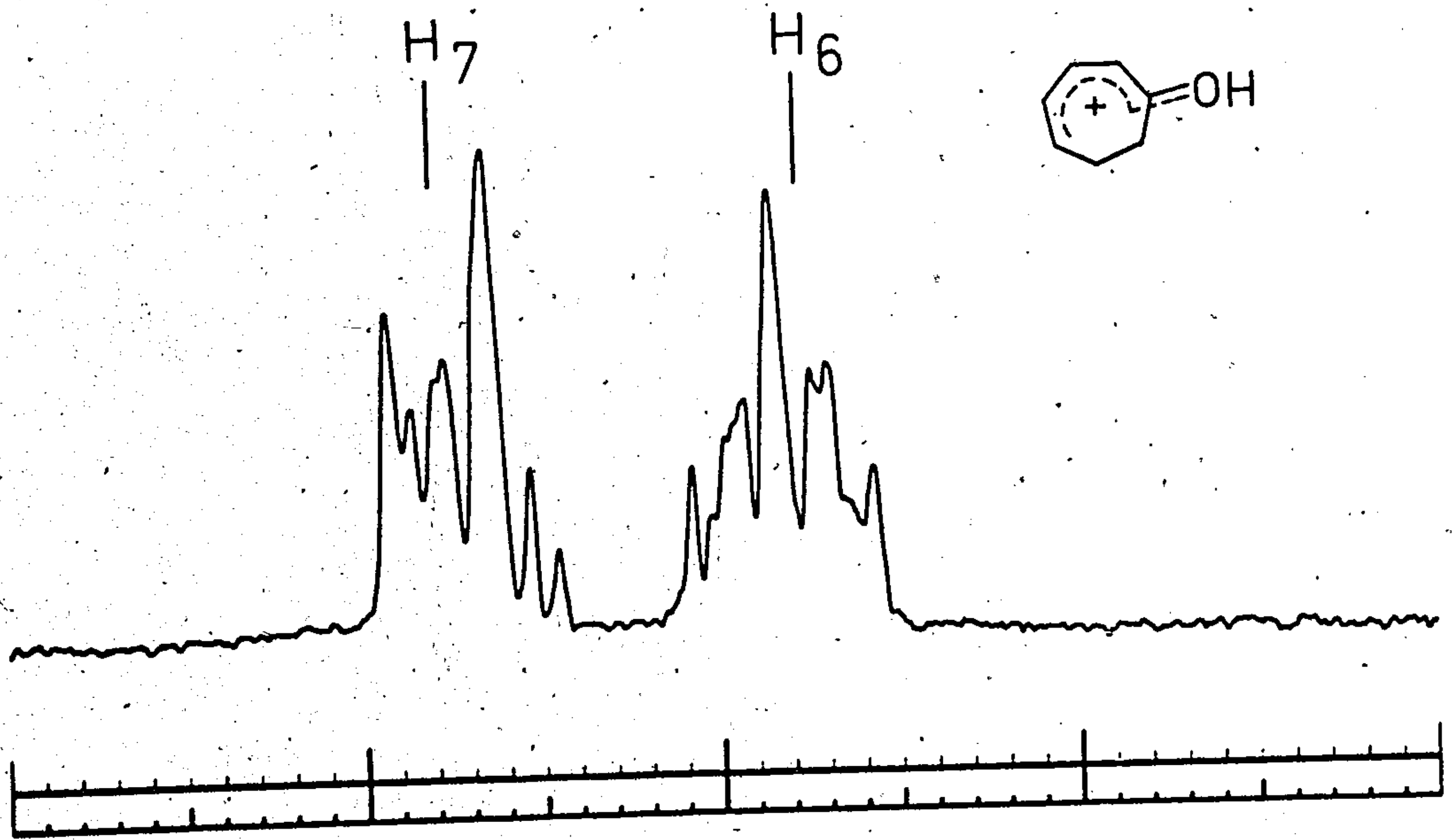


Figure 33. Effects of Decoupling H_6 on the Pmr Spectrum of <u>27H</u>

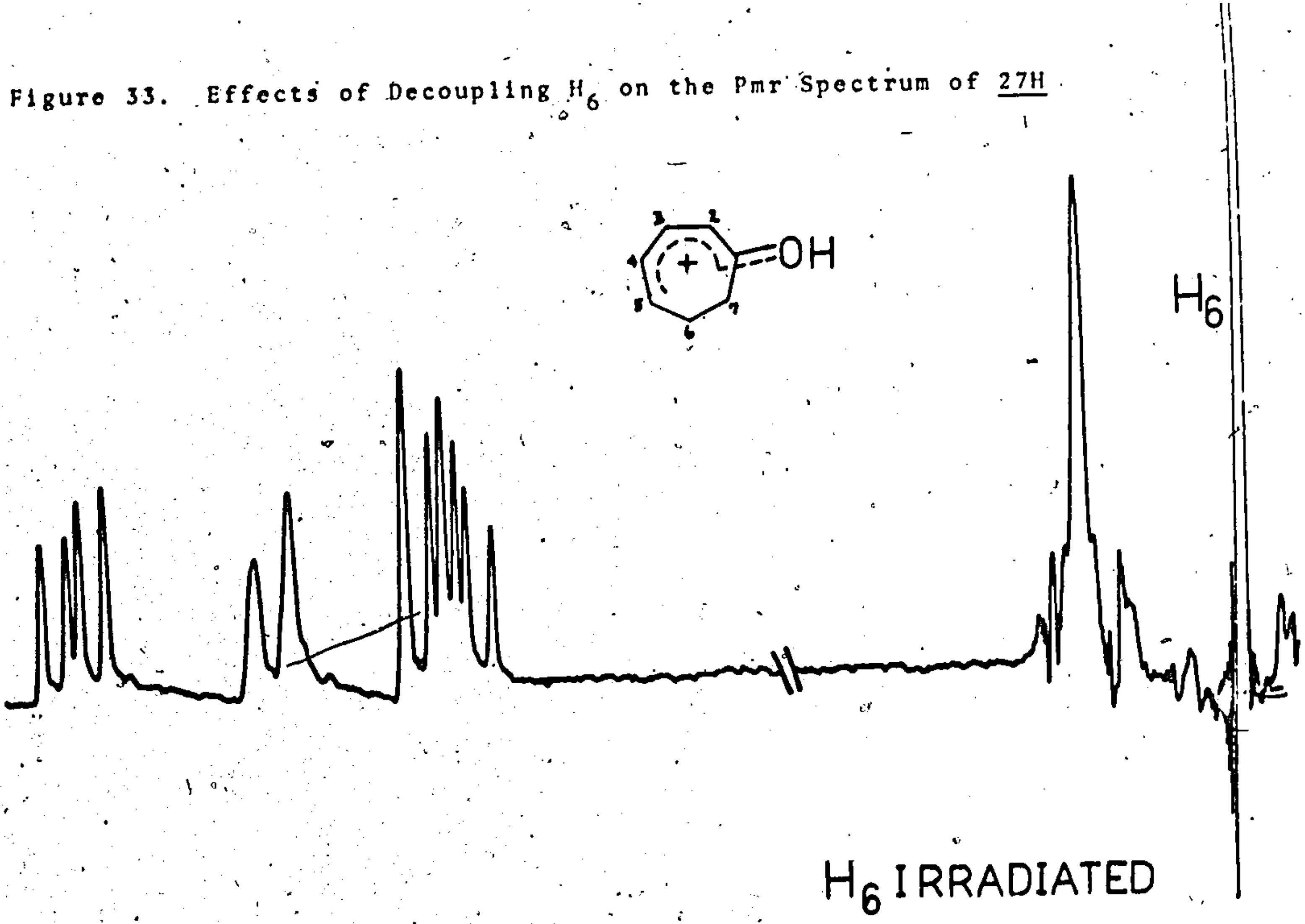
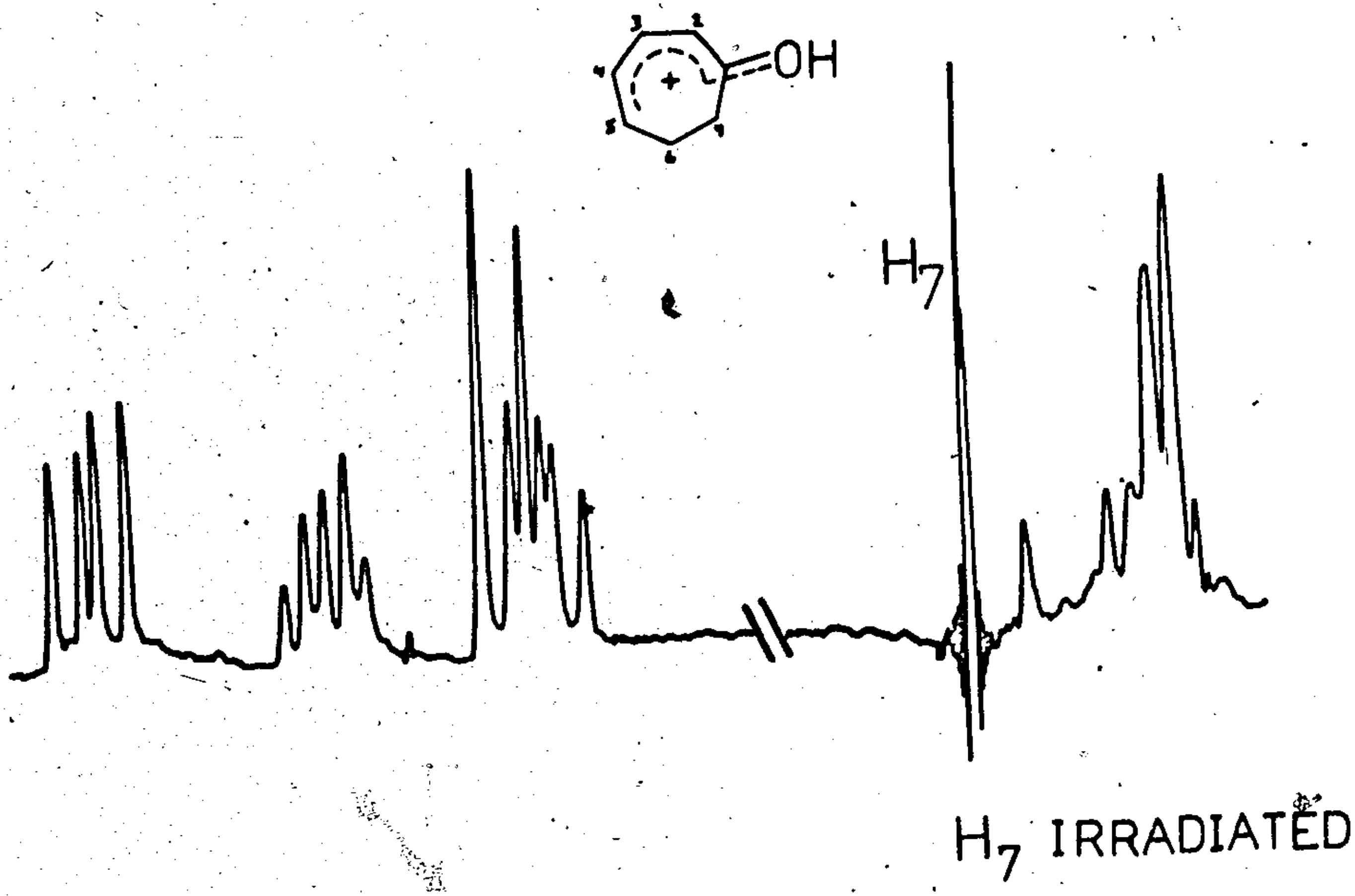
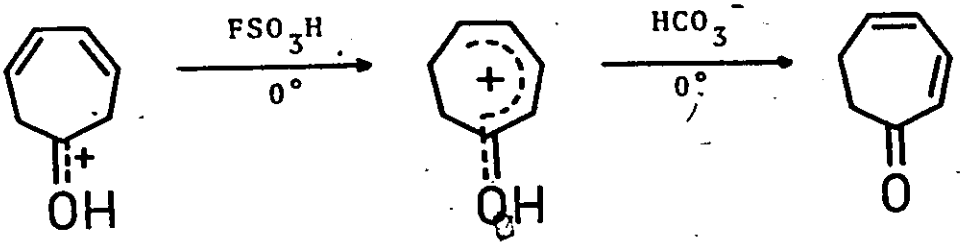


Figure 34. Effects of Decoupling H_7 on the Pmr Spectrum of <u>27H</u>

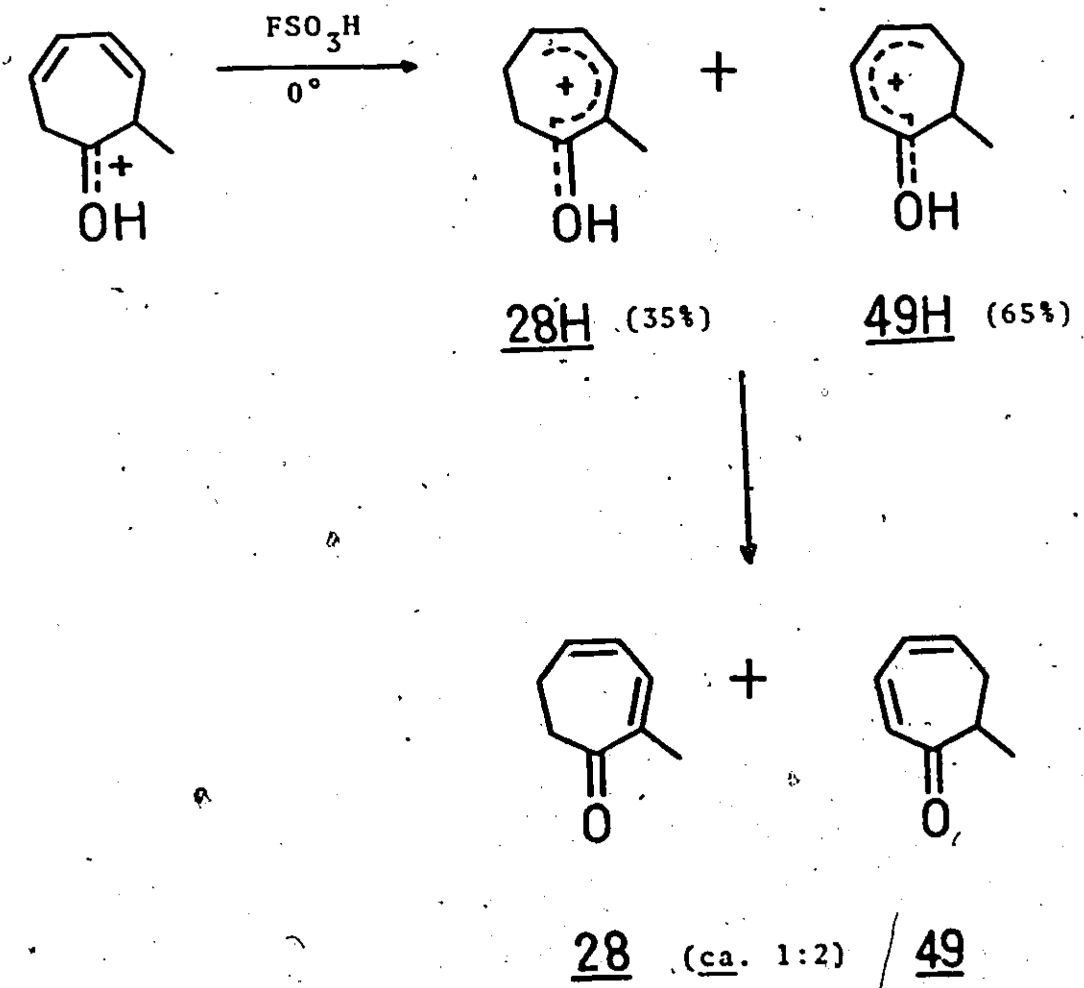




47H 27H 27

according to the procedure of terBorg.[98]

Solutions of 48H rearranged in FSO$_3$H at a somewhat slower rate at 0°, $k = 3.7 \times 10^{-4}$ sec^{-1}, to give a pmr spectrum whose vinyl region was similar to that for 27H. The high field region displayed two methyl peaks, one singlet at τ 7.74 and one doublet, J = 7.0, at τ 8.59. This suggested that both protonated 2-methyl and 7-methylcyclohepta-2,4-dienone had been formed. Quenching the solution gave an oil which glpc analysis revealed that it consisted of two products with very similar retention times. Repeated glpc separation at low temperatures (+85°) managed to yield reasonably pure compounds (>80% by pmr) whose spectral properties were consistent with 2-methylcyclohepta-2,4-dienone, 28, and the 7-methyl isomer 49. No interconversion of 28H and 49H occurred at +50° for two days in FSO$_3$H.



In contrast to the isomerization of the ketones, rearrangement of the protonated forms results in an equilibrium mixture consisting of 27H (99.5%) and 47H (0.5%). This difference in the equilibrium position must be due to a greater need for delocalization within the charged species. Since scaling up these reactions presents no problems, this reaction forms the basis for a simple and convenient preparation of 27. Attempts to extend this reaction to unsymmetrically substituted systems were without much success however, owing to the formation of isomeric products. Isomerization of 48 was studied in concentrated H_2SO_4 in an attempt to selectively produce 28.

In 96% H_2SO_4 48 was protonated on oxygen to give a solution whose pmr was identical to that of 48H in FSO_3H. Rearrangement took place at room temperature to give a seemingly complicated mixture of cations. Closer examination revealed the presence of 28H and 49H (50%) plus a new product (50%). Quenching the acid solution gave an oil which was separated by preparative glpc to give a mixture of 28 and 49 plus a pale yellow oil. The pmr spectrum in CCl_4 and FSO_3H suggested that it could be 2-methylcyclohepta-2,6-dienone, 50, (Table 20 and Figure 35). Both the ir and uv spectrum were consistent with this structure (experimental section). To confirm the structure of this product, the spectral data were compared to cyclohepta-2,6-dienone, 34, which was prepared by the standard procedure from cycloheptanone.[106] As indicated by the results in Table 20, a favourable comparison was obtained. In addition, it was shown that 47H yielded 10% of 34H in 96% H_2SO_4.

The product distribution resulting from isomerization of 48H in a series of H_2SO_4-H_2O mixtures is given in Table 21. These results are based upon the initial product ratios (reaction time ca. 30 min at 23°), as prolonged

Figure 35. The Formation of 2-methylcyclohepta-2,6-dienone from 48H in 96% H_2SO_4

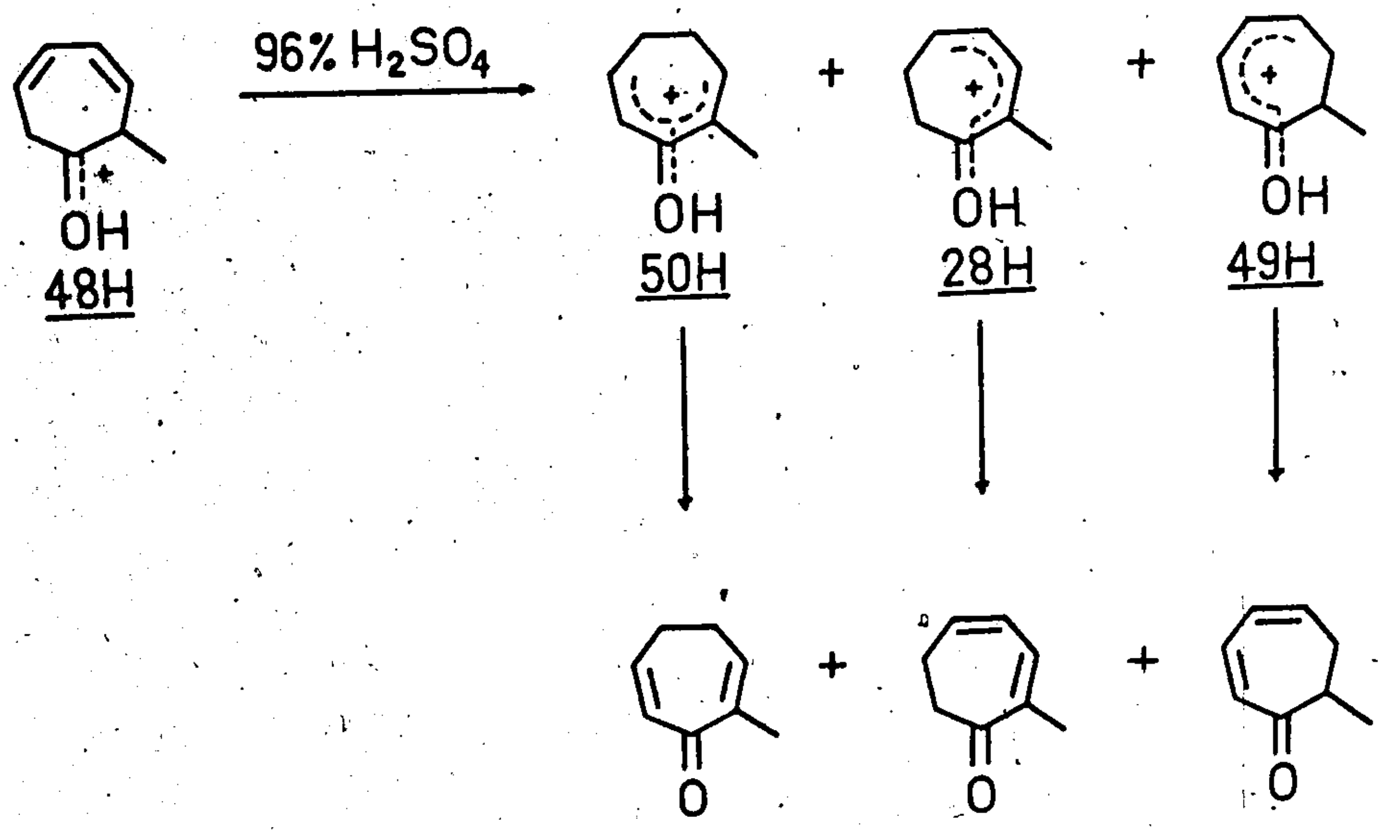


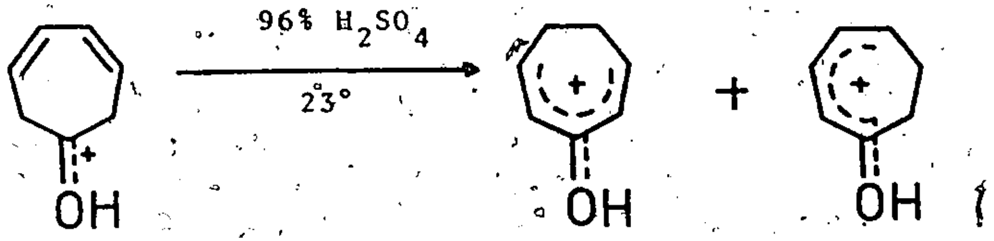
TABLE 20. Pmr Spectra of Cyclohepta-2,6-dienones and Protonated Cyclohepta-2,6-dienones[a]

Compd	H_2	H_3	H_4	H_5	H_6	H_7	Methyl	Coupling Constant
34[b]	4.10	3.50	7.57	7.57	3.50	4.10	—	$J_{2,3}$ = 12.0, $J_{3,4}$ = 2.8
34H[b]	3.26	2.05	7.16	7.16	2.05	3.26	—	$J_{2,3}$ = 12.0, $J_{3,4}$ = 3.3
50[c]	—	3.48	7.62	7.62	3.48	4.07	8.17	$J_{6,7}$ = 12.1, $J_{3,4}$ = $J_{5,6}$ = 3.0
50H[c]	—	2.05	7.17	7.17	2.05	3.21	7.80	$J_{6,7}$ = 12.0, $J_{3,4}$ = $J_{5,6}$ = 3.3

[a] Cations in FSO_3H at +37° (CH_2Cl_2). Ketones in CCl_4 (TMS)

[b] at 60 MHz

[c] at 100 MHz.



34H

For comparison sake, the results obtained for FSO_3H and FSO_3H-SbF_5 as solvents are indicated in this table. Quite clearly these reactions are unsuitable for preparative purposes.

TABLE 21. Product Distribution Resulting from the Isomerization of 48H[a]

SOLVENT	PRODUCT DISTRIBUTION In Acid[b] 28H	49H	50H	After Quenching[c] 28+49	50
96% H_2SO_4	36	15	49	50	50
86% H_2SO_4	25	11	64	35	65
74% H_2SO_4	15	8	77	20	80
FSO_3H	35	65	0	100	0
FSO_3H-SbF_5	35	65	0	100	0

---

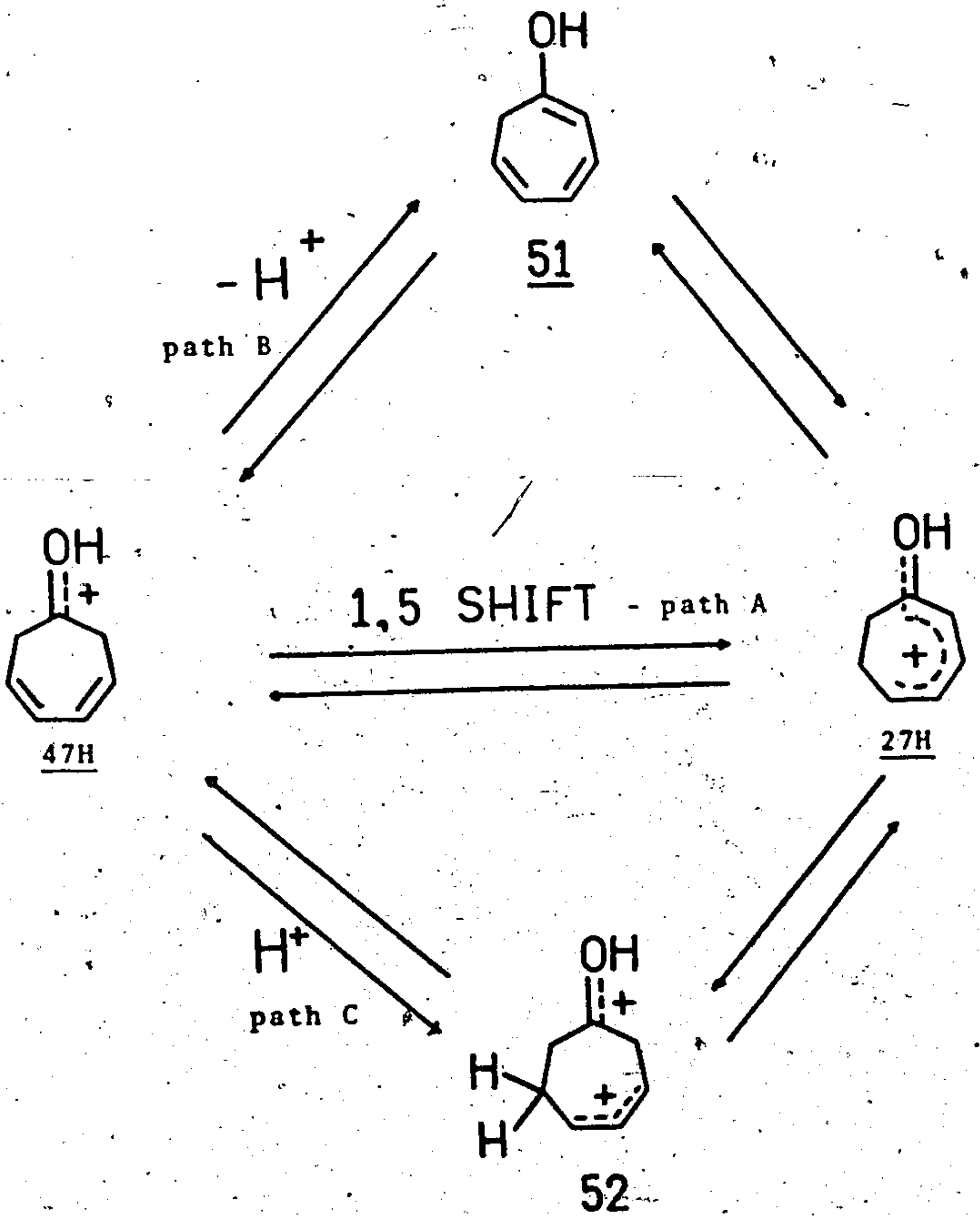
[a] At 23°. [b] Relative percentage of product cations measured by pmr. [c] Glpc analysis. 28 and 49 were not well separated under the conditions employed and are reported together.

It is interesting to note at this time that good yields (85-90%) of 2-methylcyclohepta-2,4-dienone were eventually obtained by isomerizing the 3,5-isomer on neutral aluminia, activity II at 23°. Prepared in this manner, 28 could be isolated about 95% pure (pmr), although the results were not always reproducible. This was a rather fortunate discovery which the author still fails, in a number of respects, to completely understand.

(4) THE MECHANISM OF THE ISOMERIZATION OF PROTONATED CYCLOHEPTA-3,5-DIENONE TO PROTONATED CYCLOHEPTA-2,4-DIENONE

One can suggest at least three reasonable possibilities for the mechanism of this reaction in FSO_3H. Conceivably the isomerization could proceed via a suprafacial 1,5-hydride shift as has been formulated for the somewhat analogous reactions of the neutral ketones.[98] In acid however, one might expect a stepwise process involving either initial enolization to 51 and subsequent reprotonation or an initial protonation of 47H at C_3 or C_6 to the dication 52 followed by deprotonation. These three proposals are summarized in Figure 36 and are labelled paths A, B, and C respectively. Evidence that the latter mechanism is operative in FSO_3H has been provided by deuterium incorporation studies and by acidity effects upon the reaction rate.

Figure 36: Possible Mechanisms for the Formation of 27H from 47H



In FSO_3D, 47-O-d rearranged to 27-O-d with the incorporation of a single deuterium atom at C_6. This reaction was followed by pmr spectroscopy and it was observed that the relative intensity of the high field multiplet at τ 7.18 decreased by one proton. No exchange of the C_2 or C_7 protons of 47-O-d occurred during the course of the isomerization which was run at +15° (t 1/2 ca. 30 min).

These results eliminate the possibility of an intramolecular 1,5-hydride shift. Although they appear to implicate path C, we cannot rule out the enolization mechanism on this basis, for reprotonation of the enol intermediate 51 may occur at C_6 much faster than exchange at C_2 or C_7. However, as is shown in Table 22, the rate of isomerization of 48H increased with increasing acidity of the solvent. The magnitude of the rate acceleration is within the experimental limits. The amount of SbF_5 added to increase the acidity[57] was purposely kept low to preclude any complications arising from the possibility of complexing the ketone with SbF_5.[107] This rate enhancement with increasing acidity is in accord with path C. If path B were operative one would expect that deprotonation from 48H would cause a rate deceleration.

The ratio of 28H to 49H, which did not change with solvent acidity, is consistent with the formation of dication type intermediates. Both products must arise from

TABLE 22. Rate of Isomerization of 48H in FSO_3H and FSO_3H-SbF_5 [a]

10^4 k (sec^{-1})[d]	Mole % SbF_5	H_0 [b]	Ratio 49H:28H [c]
3.7	0	-15	2.0
5.0	1.5	-18	2.0
5.4	8.5	-18.5	2.0

[a] At 0 ± 1°. All isomerizations were carried out with the same batches of FSO_3H and SbF_5 using a constant ketone concentration, 4% (wt/wt).

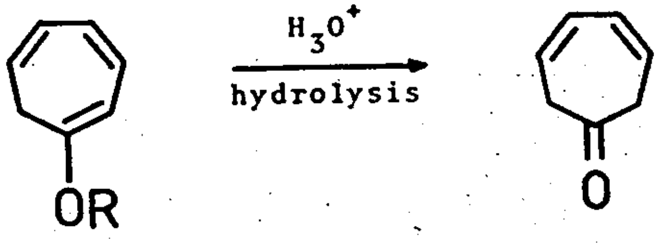
[b] See reference 57.

[c] Measured by pmr.

[d] ± 10%

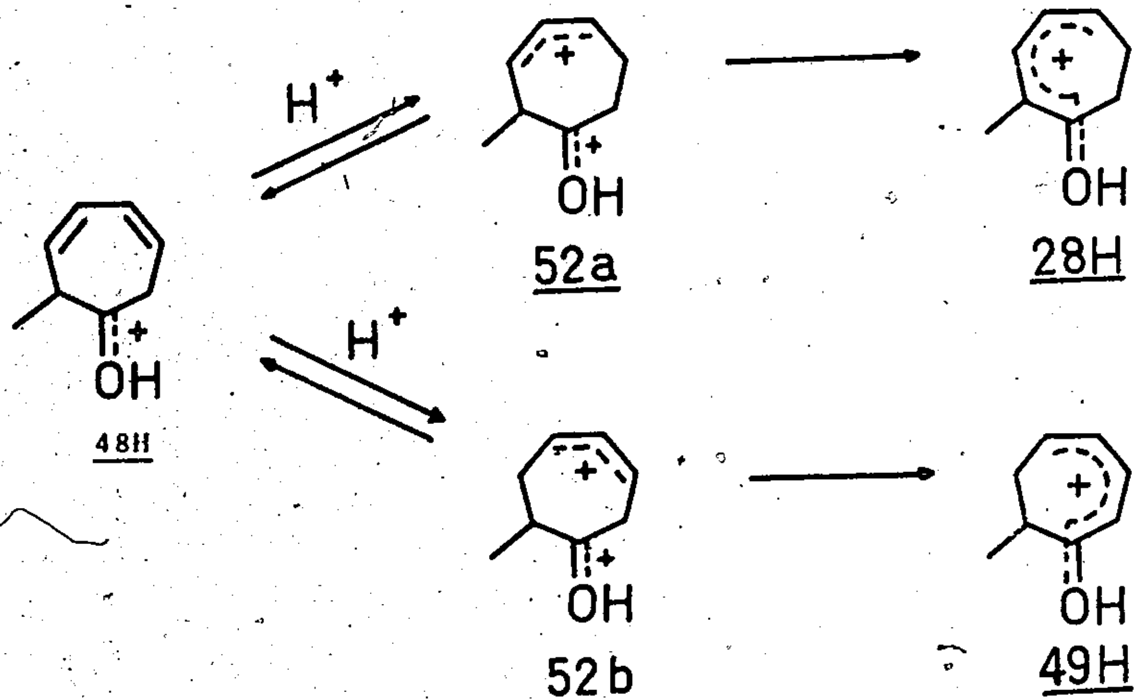
two different dications 52a and 52b respectively. The predominance of 49H could result from the greater stability of 52b, for it has been suggested that allyl cation stability decreases with alkyl substitution upon the adjacent methylene groups.[108]

The formation of an enol intermediate in FSO_3H can be further eliminated from contention by considering the following results. Both Garbisch[106] and Parham[109] have shown that acid hydrolysis of the trienol ether 53 proceeded with attack at C_2 to give cyclohepta-3,5-dienone. Somewhat related to this, Noyce demonstrated that the acid-catalyzed isomerization of cyclohex-3-enone to cyclohex-2-enone in aqueous H_2SO_4 (ca. 10-35%) involved a dienol intermediate.[101b] Deuterium exchange experiments in D_2SO_4-D_2O showed that the rate of protonation at C_2 was about 50 times the rate of protonation at the γ position. Accordingly, one might expect that the proposed intermediate 51 would preferentially reprotonate at C_2 rather than at C_6 and thus, in deuterated acid, exchange of C_2 and C_7 in 47H should have been faster



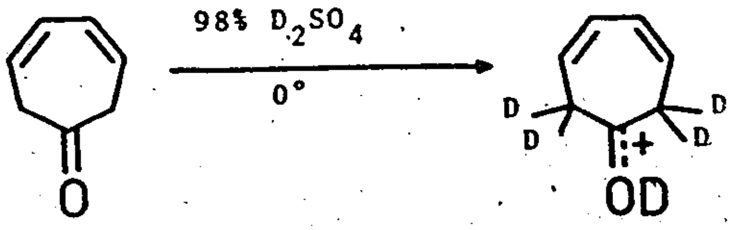
53

Thermal Isomerization of 48H in FSO_3H



than isomerization to 27H.

To test this, the reaction of 47H to 27H was run in a deuterated acid weaker than FSO_3D where enolization may be a possibility. Thus, 47-O-d in the weaker 98% D_2SO_4 underwent complete exchange of the 4 hydrogens on C_2 and C_7 without any rearrangement being detectable. This reaction was examined by pmr spectroscopy and any product less than ca. 5% would not have been observed. Conceivably, this exchange reaction would proceed via enolization and re-protonation at C_2. Perhaps the formation of cyclohepta-2,6-dienones result from subsequent reaction of an enol intermediate in concentrated sulphuric acid.



27

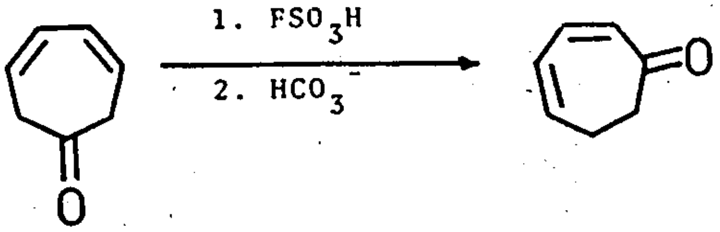
47-O-d

(5) CONCLUSION (Figure 37)

The isomerization of protonated cyclohepta-3,5-dienone in FSO_3H provides a simple and selective route to cyclohepta-2,4-dienone. Prepared in this fashion 27 is

>99% pure. Mechanistic experiments imply that this reaction proceeds through a dicationic intermediate.

Figure 37. The Preparation of Cyclohepta-2,4-dienone



PART 6. EXPERIMENTAL SECTION

EXPERIMENTAL SECTION

(1) INSTRUMENTAL

Pmr spectra were obtained on Varian HA100, A60, and T60 spectrometers, the former two being equipped with variable-temperature probes. Probe temperature was measured with a methanol sample or a thermocouple inserted into a nonspinning pmr tube containing an inert liquid. The chemical shifts in CCl_4 are referred to internal TMS(τ10.00); those in FSO_3H to internal CH_2Cl_2 (τ4.70). In all cases, the infra red spectra were recorded on Perkin-Elmer Models 521 and 337 grating spectrophotometers using NaCl or ~~KBr~~ cells. Calibration was carried out using the 1601 and 1028 cm^{-1} bands of polystyrene. Ultraviolet spectra were obtained with a Cary 14 spectrometer and mass spectra from a Hitachi Perkin-Elmer RMU-6A mass spectrometer. Varian Aerograph 204 (analytical) and Aerograph A90-P3 (preparative) gas chromatographs were used. In all cases, helium was used as a carrier gas at 50-60 ml/min. Glpc columns are referred to by a letter code: Column A, 10ftx1/4 in 10% SE-30 on Chromosorb 60-80; Column B, 12ftx1/8 in 20% Carbowax 2000 M on Chromosorb 60-80; Column C, 13ftx1/4 in 15% Carbowax 2000 M on Chromosorb 60-80; Column D, 5ftx1/8 in

5% QF-1 on Chromosorb 60-80.

Elemental analyses were performed by Galbraith Laboratories in Knoxville, Tennessee. Samples were usually sealed under vacuum in clean 1/8 in. glass tubing.

(2) REAGENTS

FSO_3H (Allied Chemicals) was distilled once from sodium fluoride (400 ml/1g) and then a second time (no NaF added) through a 12" glass column and stored in 1 ml aliquots in sealed glass ampoules. Antimony pentafluoride was distilled before use and stored in a neoprene container. Sulphuryl fluorochloride (Allied) was used as supplied. Both 96% H_2SO_4 and 98% D_2SO_4 were used as supplied. Aqueous sulphuric acid solutions were prepared by dissolving the required amount of 96% H_2SO_4 in distilled water.

Acetic Acid (3 l) was refluxed with acetic anhydride (100 ml) and distilled, bp 118°. Carbon disulphide was distilled before use bp 45°. Both carbon tetrachloride and methylene chloride were refluxed with anhydrous potassium carbonate and distilled bp 76° and 40-42° respectively. Dioxane was distilled from lithium aluminium hydride, bp 100°. Ethanol (3 l) was refluxed with magnesium (5g) and iodine (0.1g) for 24 hrs and distilled, bp 78°. Methanol was distilled in dry glassware, bp 66°. Pentane was purified by treatment with fuming sulphuric acid and distilled, bp 35-37°. Diethyl ether was used as supplied.

BUFFER SOLUTIONS

For pH values above 3.3, a buffer solution as described by Robinson was used.[110] To 100 ml of a solution 0.04 M in phosphoric and acetic acids was added varying volumes of 0.2 M sodium hydroxide: for pH 3.34, 2.5 ml; pH 4.65, 17.5 ml; pH 6.16, 31.0 ml; pH 8.86, 52.0 ml. For pH 1.62, 25 ml of 0.2 M potassium chloride was added to 67.0 ml of 0.2 N hydrochloric acid. A buffer solution of 25.0 ml of 0.2 M potassium bisulphate and 67.0 ml of 2N sulphuric acid was used for pH 0.7. The pH values, obtained using glass and calomel electrodes, are shown below. The apparent pH recorded in Table 7 is of the

pH (before dilution)	pH (after dilution with 70% MeOH)
0.02	0.70
0.95	1.62
1.95	3.34
2.90	4.65
4.70	6.16
6.95	8.86

-70% methanol solutions.

(3) GENERAL TECHNIQUES

(i) Protonations

METHOD A. For cations which were relatively stable at -78°, protonations were effected by slowly adding precooled (-78°) FSO_3H (0.5 ml) to a clean and dry nmr tube containing the cation precursor (ca. 35 mg) in a dry-ice-acetone bath. Complete solution was then achieved by agitation of the acid with a 1/16 in quartz rod.

METHOD B. The preparation of cations which were relatively unstable at -78° was accomplished as follows. To an nmr tube containing a solution (0.4 ml) of $SO_2ClF:FSO_3H$ (2:1 v/v) cooled to ca. -120° was added a solution of the precursor (25 mg in 0.1 ml CD_2Cl_2). Thorough solution was achieved as above with a precooled, -196°, quartz rod.

METHOD C. To prepare cation solutions in concentrated H_2SO_4, normally the acid (0.4 ml) in an nmr tube was cooled at -5° for at least 30 min and then to this was added a solution of the precursor (35 mg in pentane or CD_2Cl_2, 0.1 ml). Stirring to effect complete solution was performed as usual.

(ii) Quenching Acid Solutions

These techniques described below were used in pmr scale experiments (35 mg in 0.5 ml acid).

METHOD D. The acid solution of the cation was added dropwise to a rapidly stirred suspension of sodium bicarbonate (5 g) in ether (20 ml) maintained at $<-45^\circ$. Upon warming to 0°, the resultant mixture was added to ice water (5 ml), swirled, and filtered in vacuo. The ether layer was washed with brine until neutral and then dried ($MgSO_4$). Products were recovered by evaporation of the solvent and purified by chromatography.

METHOD E. For relatively stable cations, the acid solutions were neutralized by adding them dropwise to a rapidly stirred solution of $NaHCO_3$ (5 g) in ice water (25 ml) at 0°, filtering in vacuo, and then extracting with pentane or ether. Work-up was continued as in Method D.

(iii) Determination of Product Ratios

(a) By pmr. Product ratios were obtained by repeated integration of well separated ($\geq$20 Hz) signals. Normally the limit of this technique was ±5% for low temperature work and ±3% for routine samples at +37°.

(b) By analytical glpc. Product ratios were calculated by triangulation or cutting and weighing the peaks of the original chromatogram or a photocopy. Results were reproducible to ±2% in all analyses reported and generally were the average of two or three injections. Since products obtained were almost always isomeric, the reasonable assumption was made that they had identical detector responses.

(iv) Irradiation of Ketones

In the experiments on the three major ketones studied in this thesis, 6, 27, and 28, at least four separate irradiations were carried out. The first one was always of an exploratory nature to determine the length of time needed for photochemical isomerization. Having established this, the second set of experiments were conducted on a preparative scale to determine the identity of the photoproducts. Subsequent experiments were run in a more quantitative manner to examine effects of solvent polarity and acidity, product stability and any change in product ratio with irradiation time. In all cases the numbers reported in Tables were from analyses conducted on mixtures of products and starting material which were recovered in 97% yield or better.

METHOD F. A Typical Preparative Scale Irradiation

The ketone (1 g) was dissolved in a suitable solvent (100 ml) and placed in a 200 ml pyrex test tube. The resultant solution was flushed with a stream of dry nitrogen gas for at least 60 minutes and then stoppered with a cork or rubber bung wrapped in an inert material.

The pyrex vessel was suspended in the Rayonet Photochemical apparatus equipped with sixteen, 350 nm lamps and irradiated. Aliquots were withdrawn periodically to check the progress of the reaction. When the desired time had elapsed, the solvent was carefully removed and the residual oil, containing products, was purified by distillation or chromatography.

METHOD G. Low Temperature Irradiation of Protonated Ketones

All irradiations were carried out upon FSO_3H solutions contained in clear, thin-walled pmr tubes which cut off light of wavelength < 260 nm. Solutions of cations were prepared as in Method A.

Cooling Apparatus

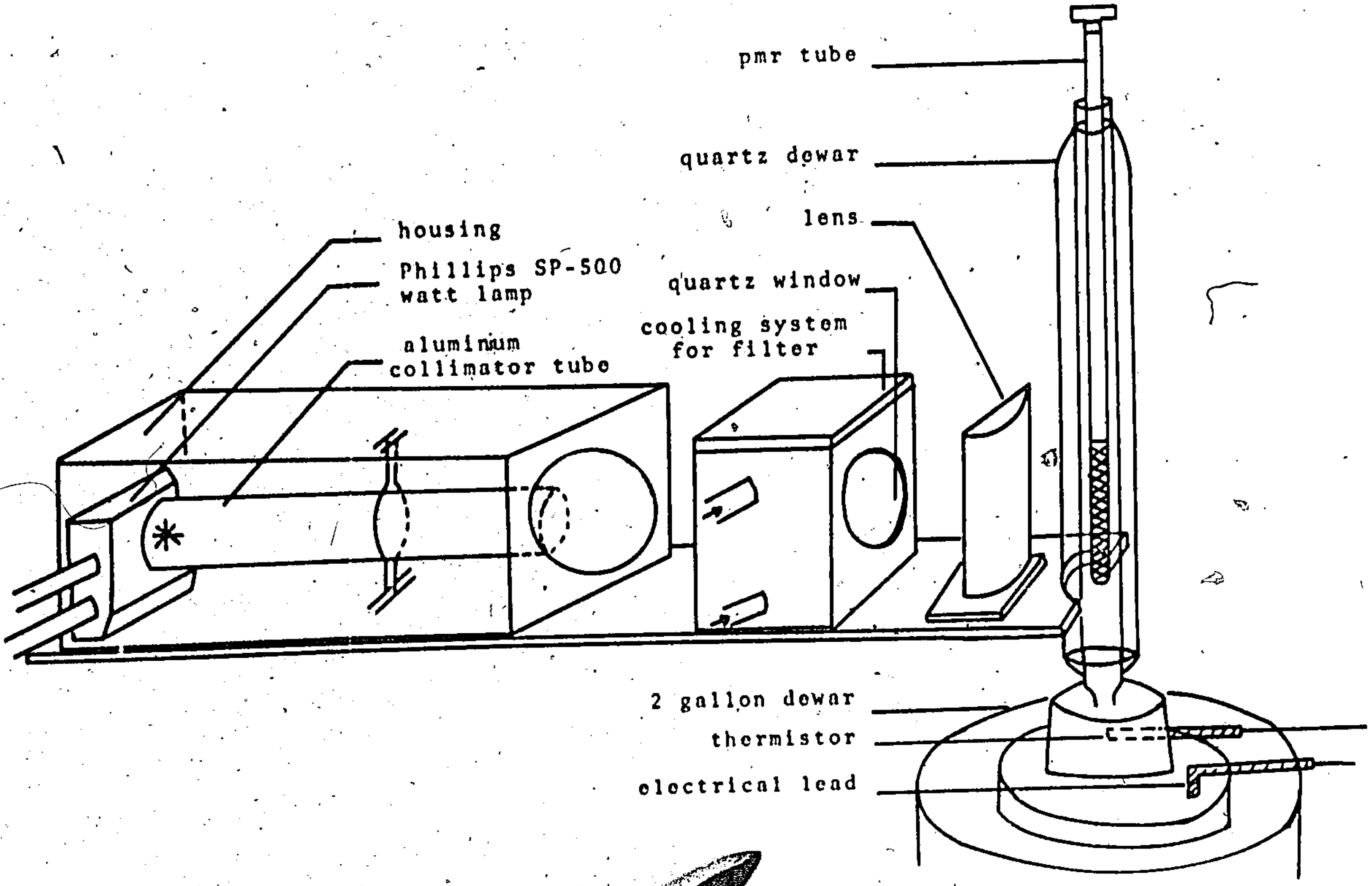
The irradiation of protonated ketones required a reasonably efficient system to maintain the solutions at low temperatures, generally between -85 and -65°. The pmr tube containing the sample was suspended in a double-walled quartz container as shown in Figure 38. This apparatus was fitted tightly into a two-holed rubber stopper which was secured in the mouth of a 2 gallon dewar of liquid nitrogen. The other hole accommodated an electrical lead from a variable-resistance power supply to a 250 watt heater placed at the bottom of the liquid nitrogen in the dewar. By passing current through the heater the liquid nitrogen was boiled up through the inside of the quartz container over the sample. The rate of boiling and hence the amount of cooling was controlled by a setting on the power supply box which governed the current passing through the heater. A thermistor, placed just below the sample, connected into the circuit, functioned to maintain a steady rate of cooling.

The temperature of the sample was measured by a copper constantan wire (thermocouple) connected to a pre-standardized potentiometer. To avoid instant solution of the wire, the tip was covered to a depth of 1" by a sealed glass capillary tube before insertion into the acid. Temperatures could be controlled to ±5° for several hours.

Irradiation Apparatus (Figure 38)

The light from a Phillips SP-500 high pressure irradiation source was concentrated along a highly polished aluminium tube, through a glass filter, and focussed by a semi-cylindrical quartz lens upon the sample. The filter used in all irradiations was a Corning #3850 which effectively cut off light of $\lambda < 370$ nm. Since the lamp produced sufficient heat to crack this glass filter, it was cooled by circulating cold water about it at a rate of about 1 l/min. For this purpose, the filter was enclosed in the aluminium box equipped with 1 1/2" diameter quartz windows.

Figure 38. Low Temperature Irradiation Apparatus



(v) METHOD H. Kinetic Studies

All rate studies were performed on solutions contained in pmr tubes. The sample was taken from a low-temperature bath (< -78°) and inserted into the probe of the nmr spectrometer whose temperature had been pre-set at the desired temperature for at least 15 minutes prior to the start of the reaction. The progress of ~~the~~ isomerization was then followed by observing the appropriate changes in the pmr spectrum with time. Rate constants were calculated for each time interval from the corrected height of a product or reactant pmr signal according to equation (3).

$$k_i = \frac{\Delta h}{\Delta t} \quad \text{sec}^{-1} \qquad (3)$$

Δh = height of signal at time t_{n+1} minus height of same peak at t_n.

$\Delta t = t_{n+1} - t_n$

The rate constant for the reaction, k, was then calculated according to equation (4).

$$k = \frac{\sum k_i}{m} \quad \text{sec}^{-1} \qquad (4)$$

m = number of k_i's determined

In most cases at least two separate runs were performed and the rate constants k calculated for each. The reported rate in each case is the average of these values. Because of the fluctuation in temperature of the pmr probe, rates could normally be reproduced to only ±10%.

(4) SYNTHESIS OF KETONES

(i) Eucarvone (6) was prepared in 66% yield from carvone (Eastman) by the procedure of Corey and Burke.[111] Ir (thin film) 3030, 2970, 2930, 2860, 1660, 1450, 1400, 1100 and 750 cm^{-1}; uv max (MeOH) 303 nm, $\log \varepsilon = 3.85$. The pmr, Table 1, was identical to that reported earlier.[112] The position of the uv max changed only slightly with solvent:

(pentane) 299, (70% MeOH) 308, (CH_2Cl_2) 300,
(60% acetic acid) 309 nm.

(ii) Tropone was synthesized by the procedure of Radlick[113] from cyclohepta-1,3,5-triene (Baker).

(iii) Cyclohepta-3,5-dienone, 47. A benzene solution of sodium bis-(2-methoxyethoxy) aluminum hydride (0.17m) was added over 1 hr to a rapidly stirred solution of tropone (9.0g, 0.85m) in anhydrous ether (400 ml) at 0°. The reaction was stirred for 1 hr at room temperature, cooled to 0° and worked up by the procedure described by

Schuster et al.[114] to give 47 as a colorless liquid, 1.5g, bp 22-24° (0.5 mm). Analysis by glpc (column D), ir and nmr showed no other isomer to be present. Ir (thin film) 3030, 2970, 2860, 1710, 1380, 1043, 892, 833 cm^{-1}; uv max (MeOH) 227 nm (ϵ 3.62).

(iv) 2-Methylcyclohepta-3,5-dienone, 48, was prepared in 72% yield by the method of Nozoe and coworkers.[99a] Distillation of the crude oil at low temperatures gave 48, a pale yellow oil, bp 23° (0.7 mm); ir (thin film) 3020, 2965, 2860, 1712, 1375, 1050, 927, 840 cm^{-1}; uv max (MeOH) 228 nm (ϵ 3.64).

(v) Cyclohepta-2,4-dienone, 27. Cyclohepta-3,5-dienone, 47 (1g) was added dropwise as a 90% solution in CH_2Cl_2 to rapidly stirred FSO_3H (10 ml) at -78°. After addition was completed, 15 min., the solution was warmed to 25° and stirred for 4 hrs. After complete isomerization had been checked by running a nmr spectrum, the acid solution was added dropwise to a rapidly stirred suspension of $NaHCO_3$ (20g) in water (50 ml) kept at -5° to 0°. The resultant mixture was extracted with ether (3 x 50 ml) - it was sometimes necessary to filter off the inorganic precipitate under vacuum to facilitate this extraction, the solid collected was washed well with ether. The combined ether extracts were washed with water until neutral and dried over

$MgSO_4$. Careful removal of the ether in vacuo gave an orange oil which was distilled through a short column to give 27, 0.8g (80%), bp 30° (0.5 mm); purity: 99.5% (pmr); ir (thin film) 3050, 2960, 2900, 1660, 1410, 1270, 685 cm^{-1}; uv max (MeOH) 294 nm (ε 3.8).

(vi) 2-Methylcyclohepta-2,4-dienone, 28. 2-methylcyclohepta-3,5-dienone (1g) was placed at the top of a 1/2" diameter column of neutral aluminia (Fischer), activity II (150g) and eluted with pet ether (bp ≤ 45°). After ten (100 ml) fractions were collected (90 min), a yellow oil was eluted in the next 100-200 ml of solvent. Evaporation of the pet ether and distillation of the oil yielded 2-methylcyclohepta-2,4-dienone (0.75g). Ir (thin film) 3040, 2980, 1653, 1435, 1360, 1228, 705 cm^{-1}; uv max (MeOH) 300 nm (log ε = 3.95).

(vii) Cyclohepta-2,6-dienone, 34 was prepared by the four step procedure from cycloheptanone reported by Garbisch.[106] Pmr (Table 20). Ir (CCl_4) 3032, 2928, 1648, 1610, 1405, 1080, 860, 790 cm^{-1}.

(viii) Bicyclo[2.2.1]hept-5-en-2-one was prepared by the procedure described by Cristol[115] from bicyclo[2.2.1]hept-5-en-2-01 (Aldrich). bp 32-36° (10 mm). Ir (thin film) 3070, 2975, 2948, 1748, 1325, 992, 858, 770 cm^{-1}. Pmr

(CCl_4) 2H (vinyls τ 3.55, 3.94); 2H (bridgeheads) τ 6.86, τ 7.13; 4H τ 7.8-8.4.

(ix) Bicyclo[3.2.0]hept-3-en-6-one was obtained from the irradiation of bicyclo[2.2.1]hept-5-en-2-one according to the procedure of Schuster.[116] Purification was easily effected by chromatography on basic aluminia. Ir (CCl_4) 1780 cm^{-1}; pmr (CCl_4) 2H (vinyls) τ 4.13, 4.40; 1H (bridgehead) τ 5.79; 5H τ 6.6-7.8.

(x) Bicyclo[2.2.1]hept-2-en-7-one was donated by Professor J. Warkentin. It was prepared by Drs. F. Clark and S. Korn by a standard procedure.[117]

(xi) 2-Methylcyclohepta-2,6-dienone, 50. 2-methylcyclohepta-3,5-dienone, 48, (1.0 g) dissolved in CH_2Cl_2 (1 ml) was added dropwise to rapidly stirred 96% H_2SO_4 (8 ml) at 0°. The solution was stirred for 1 hr at 25°. After this time, the resultant solution was worked up by adding it to excess $NaHCO_3/H_2O$ at 0° as previously described. Distillation of the yellow oil obtained gave 0.92g (bp 34° at 0.6 mm) of a mixture of 28 (45-50%) and 49 and 50 (50-55%). Preparative glpc (Column C)readily gave 50 0.4g (40%) 99% purity; ir (thin film) 3035, 2930, 1650, 1615, 1435, 1405, 1378, 1280, 1220, 1080, 865, 792 cm^{-1}; uv max (EtOH) 240 nm (ϵ 3.89), 275 nm (ϵ 3.40); mass spectrum (70 ev) m/e (rel intensity) 122 (90), 107 (25) and 79 (100).

Anal. Calcd. for C_8H_8O; C, 78.65; H, 8.25. Found C, 78.60; H, 7.99.

(5) EXPERIMENTS

(i) (a) Preparative Scale Irradiation of Eucarvone in 60% Acetic Acid

Compound 6 (1.5g) was dissolved in 60% acetic acid (125 ml) and irradiated according to the procedure of Method F. After 24 hours analysis showed 10% reaction. The solvent was distilled off to leave an oil (1.3g) which was vacuum transferred to give a mixture of 6 and products, free of acetic acid and any non-volatile components (1.0g). This oil was separated by preparative glpc (columns A and C) to yield eucarvone and six products. Enough of each was collected for spectroscopic identification (15-40 mg). The pmr spectra of 7, 8, 9, 10, 11, and 12 are recorded in Tables 4 and 5. Ir spectra (CCl_4) $\nu_{c=0}$: 7 1732 cm^{-1}; 8 1730 cm^{-1}; 9 1782 cm^{-1}; 10 1740 cm^{-1}; 11 1665 cm^{-1}; 12 1775 cm^{-1}. The retention times (min) of each product on column C 135°, 60 ml/min He, were 43, 72, 37, 59, 79, and 48 respectively.

(b) Preparative Scale Irradiation of Eucarvone in Buffered Methanol-Water Solution

Eucarvone (2.0g) in pH 0.7 solvent (150 ml) was irradiated at 350 nm according to Method F. After 18-20 hours the solution was poured into water (200 ml) and extracted with ether (3x50 ml). The organic layer was washed with brine until neutral to pH paper and dried ($MgSO_4$). Evaporation of the solvent left 1.8g of an oil which was distilled to remove solvent and any non-volatiles. Analysis (column B) showed 6 (90%), 7 → 12, plus another product identified as 17. Compound 17 was collected by preparative glpc as an oil: pmr Table 23; ir 3550 - 3150, 3040, 2948, 2930, 2870, 2818, 1640, 1582, 1440, 1455, 1348, 1358, 1240, 1200, 1028, 940 cm^{-1}. Anal. Calcd for $C_{11}H_{17}O_2$: C, 72.47; H, 9.94. Found: C, 72.28; H, 9.81. Compounds 7 → 12 were identified on the basis of their glpc retention times in comparison to authentic materials.

(ii)(a) Low Temperature Irradiation of Protonated Eucarvone

Samples of 6H (35 mg) in FSO_3H (0.4 ml) were irradiated in pmr tubes at < -65° for between one and two hours according to Method G. In each case the progress of the reaction was monitored by pmr. The acid solutions of the products were quenched at -45° in ether-bicarbonate as described in Method D. The oil obtained in each run was separated into three components by preparative glpc and collected as oils. Identification was carried out by

TABLE 23. Pmr Spectra of Photoproduct 17[a]

Ring Protons				Methyls			Hydroxy	Coupling Constant[b]
H_3	H_4	H_5	H_7	C_2	C_6	OCH_3		
4.43	6.17	7.91	8.08	8.26	8.73	6.87	6.70	$J_{3,4} = 1$, $J_{4,5} < 0.5$,
			8.33 (J=1.7Hz)		9.17			$J_{7,7'} = -12.0$

[a] HA100 MHz at + 37°. Assignments made using double and triple resonance experiments

[b] ± 0.3 Hz.

spectroscopic techniques. Compound 11: (75% of mixture); pmr Table 4; ir (CS_2) 3015, 2950, 2930, 1665, 1390, 1285, 1250, 1120, 1050 cm^{-1}; Compound 13: (20% of mixture); pmr Table 4; ir (CS_2) 3600, 2960, 2930, 1300, 1230, 1172, 1115, 995, 938, 860, 812, 712, 694, 638 cm^{-1}; mass spect, m/e 150(78), 135(80), 107(100). (Relative intensity in brackets.) Authentic carvacrol purchased from J. T. Baker Co. had identical pmr and ir spectra; Compound 14: (5%); pmr Table 4; ir (CS_2) 3022, 2960, 1715, 1398, 1345, 1286, 1250, 844 cm^{-1}. Anal. Calcd for $C_{10}H_{14}O$: C 79.96; H, 9.39. Found: C 79.98, H 9.44. Uv, $\lambda_{max}^{CH_3OH}$ 236, log ϵ = 3.75.

By using internal TMAC as a standard in these irradiations it could be established that ca. 5% material loss occurred. This was accomplished by obtaining the ratio of the height of the methyls in 6H to that of TMAC at the start and comparing it to the sum of the methyl peaks of the products to the same TMAC peak at the end of the irradiation. In addition, the crude mixture of 11, 13, and 14 obtained as described above could be reprotonated in FSO_3H at -78° to give a pmr spectrum which was identical in composition to that obtained upon photolysis of 6H. The ratio of 11H:13H:14H measured by pmr (15:4:1) was similar to that of 11:13:14 measured by glpc (75:20:5). The yields of recovered oil from quenching the acid solution were between 80-90% based on weight of recovered products verses weight of starting material. Considering the evidence above, it is felt that losses occurred during work-up.

(ii) (b) Small-Scale, Low-Temperature Irradiation of 6H

Compound 6 (3-4 mg) was dissolved in FSO_3H (0.4 ml) at -78° and irradiated at -65° for 15 minutes according to Method G. After this time, the sample was quenched immediately in a suspension of $NaHCO_3$ (5 g) in ether (15-20 ml) at -75°. Upon warming to room temperature the resultant mixture was filtered, washed with water (3x5 ml) and dried ($MgSO_4$). The ether layer was then filtered and carefully evaporated to 0.1 ml. Analysis by glpc on column B showed 9 (1.5%), 14 (0.5%), 6 (50%), 11 (40%), and 13 (8%). In separate runs on the same scale, the irradiated solutions were placed in the probe of the pmr spectrometer (-45°) for 15 minutes before quenching. This was intended to duplicate the conditions used for larger scale experiments. After this time, the solutions were worked up as above and analyzed by glpc. Under the same conditions on column B the recovered oil was shown to consist of 9 (<0.5%), 14 (2%), 6 (50%), 11 (40%), and 13 (8%).

(iii) Control Experiments for (ii)

(a) Low Temperature Irradiation of 11H

Compound 11 (20 mg) was dissolved in FSO_3H at -78°

(Method A) and irradiated for 30 minutes at < -65° using light of λ>370 nm, Method G. No change was observed by pmr. This irradiation was repeated for the same time with no detectable isomerization. However, when <u>11H</u> was photolyzed with light of wavelength > 280 nm, a reaction took place after one hour to give a product whose pmr spectrum in FSO_3H was identical to that of <u>13</u>. Other minor products (5-10%) were not further investigated.

(b) Thermal Stability of Eucarvone Photoproducts <u>7</u> → <u>14</u> in FSO_3H

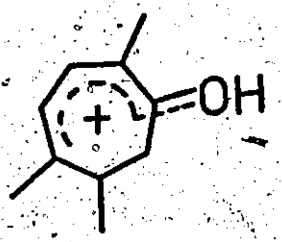
Each ketone (<u>ca</u>. 20 mg) was dissolved in the super acid media according to Methods A or B. The resultant solutions were examined by pmr at various temperatures between -85° and <u>ca</u>. -10°. Normally, the probe temperature was increased from the lowest value by increments of 10° until an isomerization took place. Isomerizations were followed by pmr spectroscopy in all cases and rates were evaluated from the changes in a peak of a reactant compared to an internal standard such as dioxane or CH_2Cl_2. In general, a cation was deemed "stable" if it did not change at temperatures > -30° for at least 30 minutes. Products were identified as described in the results section (II - iii)

(c) Thermal Isomerization of Protonated Bicyclo[3.2.0]hept-3-en-6-one

This experiment was carried out as above in FSO_3H:SO_2ClF at -75°. The product cation, 27H, was identified by its pmr spectrum in comparison to material synthesized as described earlier.

(d) Thermal Isomerization of 12H

Compound 12 (20 mg) was protonated as in Methods A and B. In each case, isomerization took place at -55° to a new cation identified as 16H. The pmr spectrum of 16H at -30° consisted of two vinyls τ2.21 and τ3.46, J = 9.4 Hz which were assigned to C_3 and C_4 respectively on the basis of chemical shifts in comparison to those of 6H and 27H. The remainder of the spectrum is shown below. Quenching the acid solution gave an oil whose spectral properties were consistent with 16. Ir (CCl_4) 3035, 2965, 2930, 1665, 1600, 1455, 1378, 1260, 1250, 1208, 1090, 1000, 865 cm^{-1}. Uv $\lambda_{max}^{CH_3OH}$ = 310 nm, log ϵ = 3.7.



16H

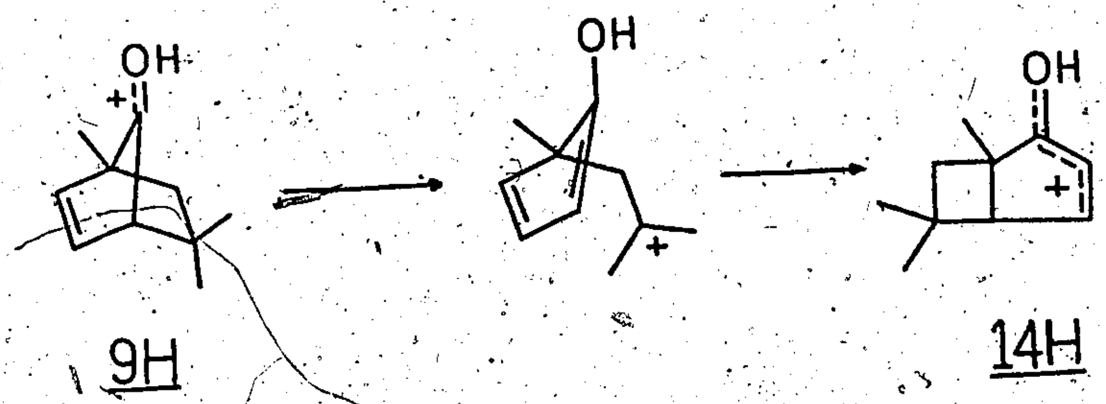
Pmr Spectrum of 16H

Methyls	τ7.72, 7.86, 8.91 (J = 7.2 Hz)
Vinyls	τ2.21, 3.46 (J = 9.4 Hz)
Other	τ7.21, 7.03 (H_7) (J = 17.5 Hz)
	τ6.51 (H_6) ($J_{6,7}$ = 7.0 Hz)

(e) Thermal Isomerization of 9H

Compound 9 was protonated at -78° in FSO_3H (20 mg in 0.4 ml) according to Method A. At -55° C, 9H underwent an isomerization to 14H, identified by its pmr spectrum in comparison to that of authentic 14H. This solution was quenched as in Method D to give an oil whose ir and glpc retention time, column B, was identical to that of 14. No other product could be detected (2% limit).

The isomerization of 9H to 14H can be viewed as taking place by the process shown below. It is interesting that in the absence of the gem-dimethyl group at C_5, no analogous isomerization took place. For example, 30H decomposed at temperatures greater than -20°. Similar types of rearrangements to that of 9H → 14H have been reported in the literature.[118]



9H

14H

(f) Thermal Isomerization of 11H

Compound 11 was protonated at -78° in FSO_3H (25 mg in 0.4 ml) according to Method A. At -16°, 11H isomerized to a new cation whose pmr was identical to that of 13H.

(g) Thermal Isomerization of 7H and 8H

Compound 7 (25 mg in 0.1 ml CD_2Cl_2) was protonated in $SO_2ClF:FSO_3H$ (2:1) at ca. -100° and examined by pmr at -85° about 5 minutes later. The spectrum obtained was identical to that of 8H formed in the same manner. Cation 8H isomerized at -45°, $k = 2.5 \times 10^{-2}\ sec^{-1}$, to a new cation which displayed principal pmr signals at τ6.35, (2H), τ7.22 (3H), τ7.37, τ7.56, τ8.91 (3H). Quenching the acid solution of this product yielded an oil which was subjected to glpc analysis, column B, 155°. Three peaks had retention times of 43, 59, and 73 minutes. Under these conditions, 14, 11, and 13 had retention times of 25, 42, and 55 minutes respectively. Each of the three products were collected by preparative glpc. The complete ir spectrum of each compound did not match those of 14, 11, or 13.

(h) Thermal Isomerization of 17 in Strong Acid

Compound 17 (35 mg in 0.1 ml CD_2Cl_2) was dissolved in $SO_2ClF:FSO_3H$ at -110° and reacted very rapidly at <-75° to give 9H as judged by pmr. At -45° 9H was cleanly isomerized to 14H.

(i) Hydrolysis of 7, 9, 11, and 17 in pH 0.7 Buffer

The same procedure, as outlined below, was followed for each compound. Approximately 10-20 mg of each reactant was dissolved in 3-5 ml of pH 0.7 buffer and refluxed on a steam bath for 45 minutes. These conditions for hydrolysis would be much more extreme than the irradiation conditions (30 min at ca. +30°). Each solution was worked-up by pouring into saturated $NaHCO_3$ solution (5 ml), extracting with ether (3x5 ml) and drying ($MgSO_4$). The ether layer was filtered, evaporated to 0.1 ml and the product examined by glpc, column B.

(j) Thermal and Photochemical Stability of 10H

Compound 10 (25 mg) was protonated in FSO_3H (0.5 ml) according to Method A. After one hour at -25° no change in the pmr spectrum of 10H was observed. Similarly, after 6 hours of irradiation at -75° using light of $\lambda > 280$ nm no change was detected by pmr. Quenching the solution (Method C) recovered white crystals (20 mg). Glpc analysis, column B, showed only one peak with an identical retention time to that of 10.

(iv) Product Ratios as a Function of Solvent Polarity

Into each of a number of 25.0 ml volumetric flasks was weighed 100.0 ± 0.5 mg of 6. Each flask was filled to the mark with a N_2 flushed solvent. Aliquots (10.0 ml) were taken from each and placed into pyrex test tubes and sealed under N_2. Irradiations were carried out in the Rayonet at 350 nm using a merry-go-round apparatus. After $\leq 5\%$ reaction the solvents were evaporated to give in each case an oil (40 ± 2 mg) which was analyzed by glpc, column B. Solvent polarity had an effect upon the rate of isomerization ($\phi_{rel}^{Benzene} / \phi_{rel}^{MeOH} = 14$) so not all analyses were conducted after the same period of irradiation time.

(v) Product Ratios as a Function of Solvent Acidity

The solutions of 6 were prepared as above using the buffered methanol solvents. Irradiations were carried out. as above in the MGR apparatus and were exposed to the light for the same length of time (30 min). Work-up by procedures described earlier yielded in each case an oil (98-100%). Glpc analysis using chlorobenzene as internal standard was performed using column B.

(vi) Quenching Experiments

A solution of 6 (192 mg) and cycloheptanone (8.2 mg) in 96% dioxane - 4% water was made up in a 10 ml volumetric.

2.0 Ml aliquots of this solution were pipetted into each of 5 pyrex test tubes (10 ml) containing 0, 1.5, 2.8, 5.5, and 10.3 µl of cyclohexa-1,3-diene. After shaking well to effect uniform solution, the tubes were placed in the MGR apparatus and irradiated for 8 1/2 hr at 350 nm. The solutions were analyzed by glpc, column B at 138°, by directly injecting the solutions into the chromatograph. This avoided any losses in work-up. The amount of 7 produced in each case was measured relative to internal cycloheptanone. The low extinction coefficient of this standard ($\epsilon = 9.83$, $\log \epsilon = 0.86$ at 313.0 nm[119]) insured that it would not have undergone any reaction under the present conditions.

This experiment was repeated several times using various amounts of cyclohexa-1,3-diene as quencher.

Quenching in acidic solvents was done in exactly the same fashion except that solutions were worked-up and the oils recovered before glpc analyses.

(vii) Emission Studies

Fluorescence studies were performed with an Aminco-Bowan spectrofluorimeter using 10^{-1} - 10^{-3} M solutions of eucarvone in purified pentane or aqueous acetic acid. All solutions were degassed for at least 1/2 hr with a steady stream of argon gas. Experiments employed excitation wavelengths between 250 and 300 nm with maximum sensitivity of the instrument.

Phosphorescence studies were carried out on the same instrument modified with an attachment for low temperature work. At 77° K no emission from 6 in 1:1 ethanol-ether glass or 96% H_2SO_4 glass could be observed.

Under the conditions employed above, emission from naphthalene and benzophenone respectively could easily be observed.[120]

(viii) Photoisomerization of Cyclohepta-2,4-dienone

Compound 27 (200 mg) was dissolved in methanol (25 ml) and irradiated for 8 hours according to Method F. The solvent was carefully distilled off at atmospheric pressure through a 6" vigreux column and the oil (180 mg) subjected to glpc analysis, column D, at 85-90°. Only two peaks were observed corresponding to 27 (5%) and the photoproduct 29 (95%). Compound 29 was collected by preparative glpc, column A, and identified by standard spectroscopic techniques. The mass spectrum showed a molecular ion, $^m/e$ 108 (100) and a relatively strong peak due to loss of CO, $^m/e$ 80 (64). The ir displayed an intense carbonyl absorption at 1730 cm^{-1} which is typical of a saturated ketone in a medium size ring,[65] and is almost identical to those reported[42] and obtained for 7 and 8.

Other bands at 3050, 2960, 1268, 1245, 1060, 1032, 820, and 685 cm^{-1} agreed well with those reported by Story for 29 prepared in a different manner.[80] The pmr spectrum, Table 12, was fully consistent with the assigned structure. I have reproduced the pmr spectra of 29, 31 and 7 in Figures 39, 40, and 41, respectively to somewhat accentuate their similarities and to facilitate the discussion. Two vinyl hydrogens formed an AB quartet whose coupling constant, $J = 2.8$ Hz, was identical to those reported by Paquette[121] for cyclobutenes in bicyclo[3.2.0]hept-6-ene systems. The positions of the vinyls at τ 3.75 and τ 3.96 were indicative of non-conjugated olefinic protons. The two bridgeheads were assigned to the multiplets at τ 6.43 and τ 6.97 on the basis of their similar positions to those of 7 and 8. Four other protons were found at higher field and formed an extremely complex pattern which decoupling did not significantly simplify.

Other possible photoproducts of 27 shown below were synthesized and it was found that their glpc retention times on column D were sufficiently different from that of 29 and 27 to allow detection if they were formed. A product >1% could easily have been detected under the conditions. Unfortunately the product corresponding to 11 was not readily available for comparison sake. It is felt that it would have readily survived the glpc conditions to be

Figure 39. Pmr Spectrum of Bicyclo[3.2.0]hept-6-en-2-one

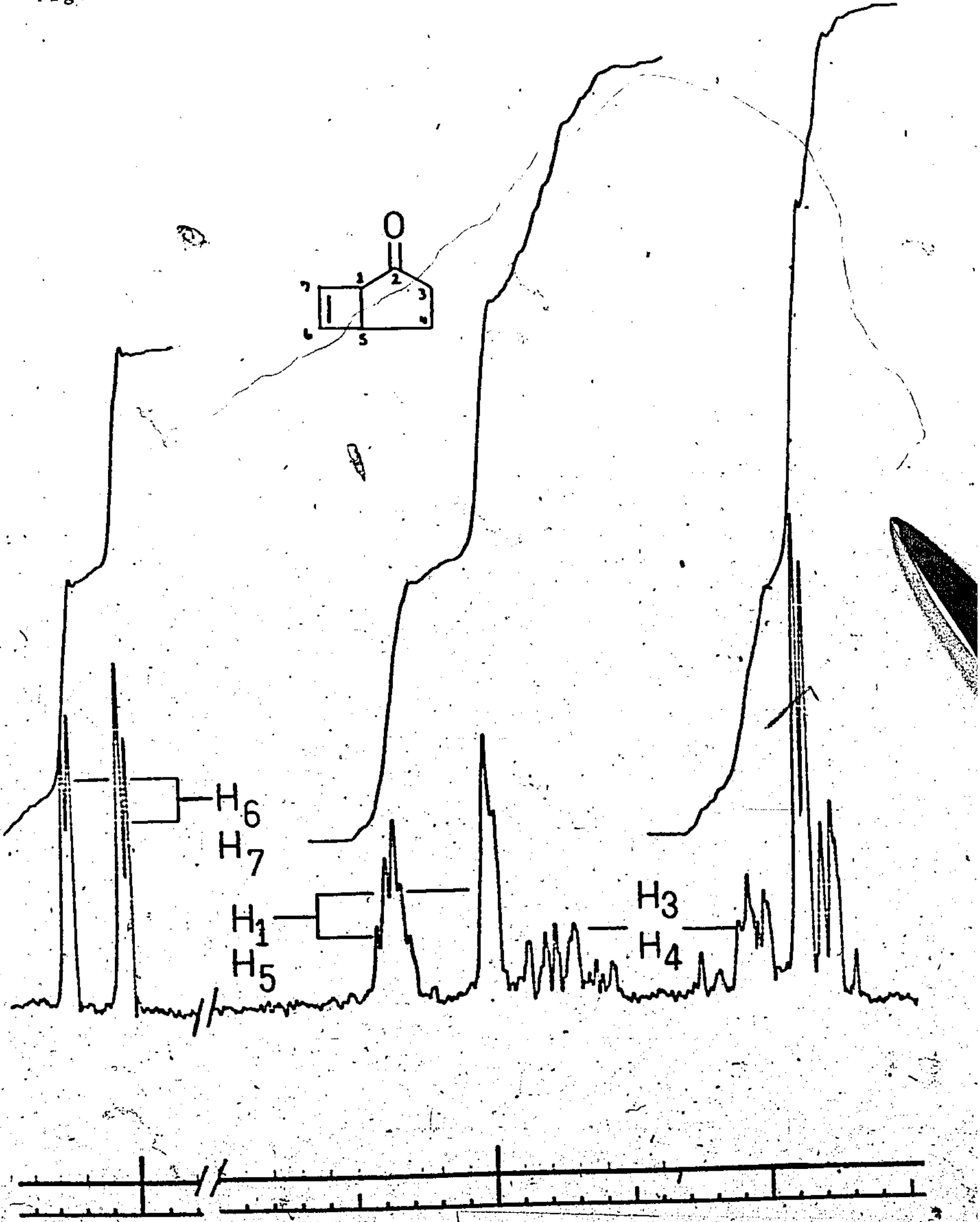


Figure 40. Pmr Spectrum of 1-methylbicyclo[3.2.0]hept-6-en-2-one

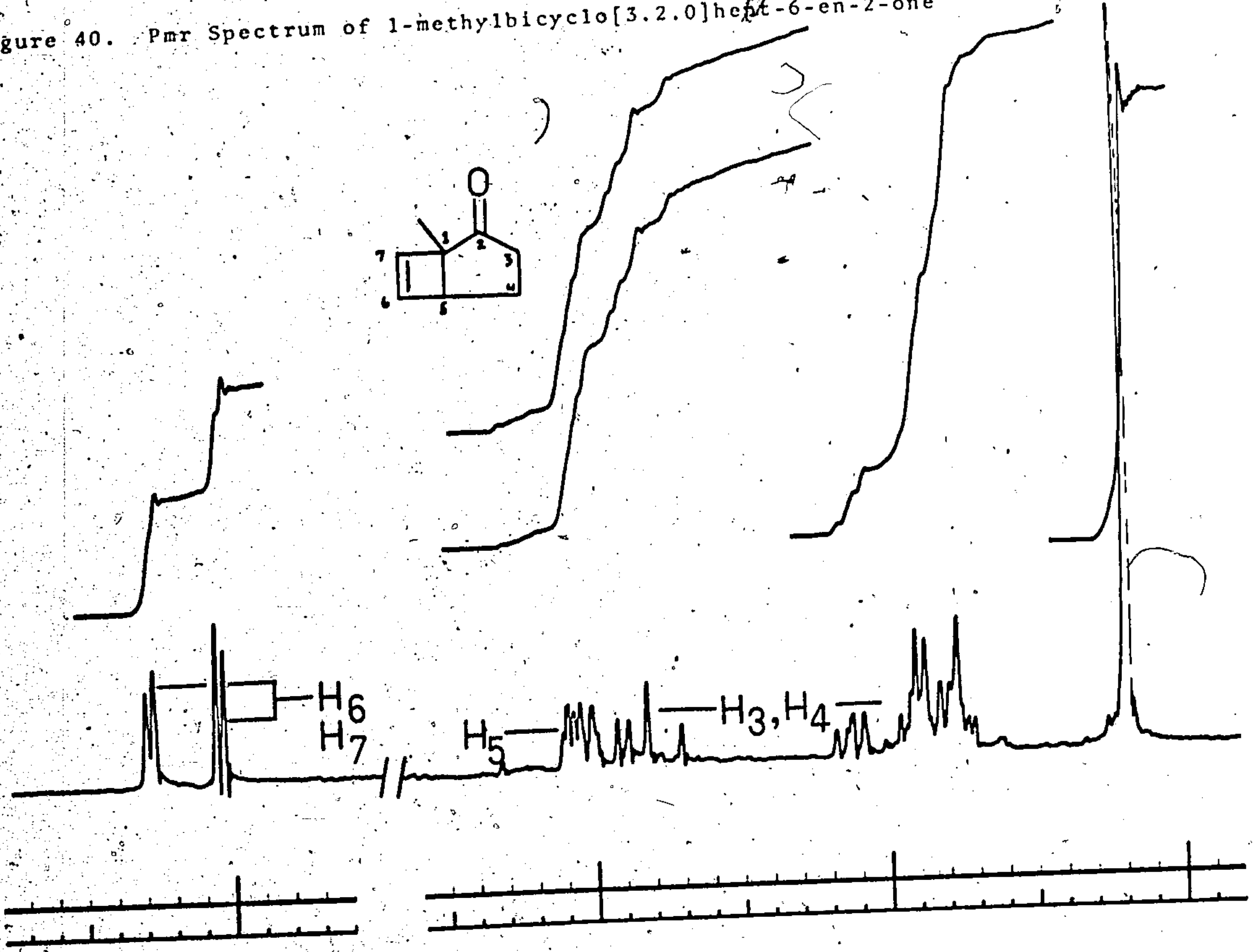
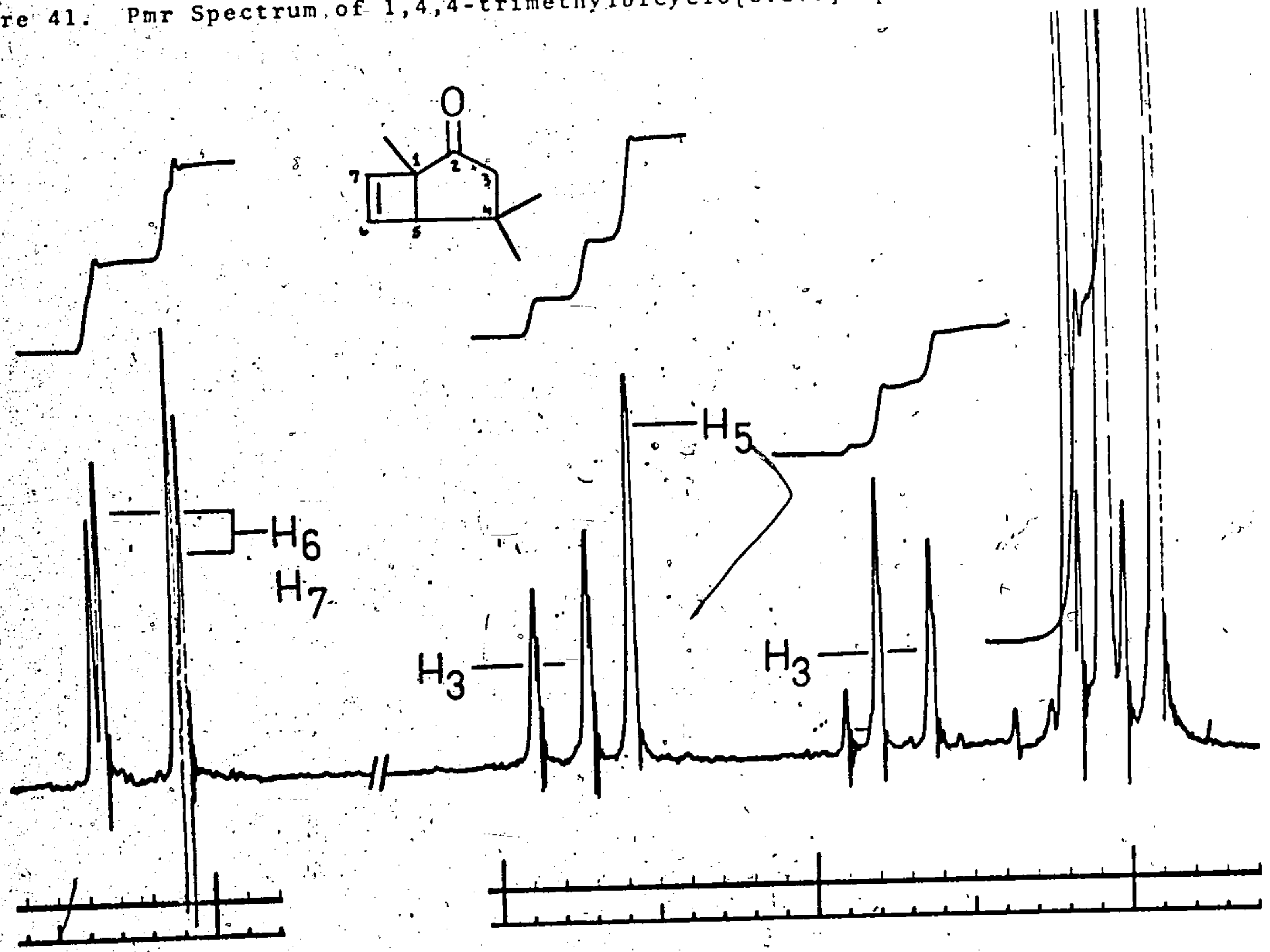
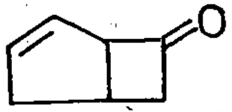
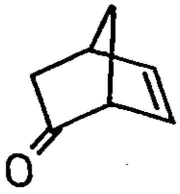


Figure 41. Pmr Spectrum of 1,4,4-trimethylbicyclo[3.2.0]hept-6-en-2-one





bicyclo[3.2.0]hept-5-en-3-one



bicyclo[2.2.1]hept-5-en-2-one

detected. As well, when samples of 27 were completely irradiated, no peak between 1660-1670 cm^{-1} expected for this product could be detected in the ir spectrum of the crude oil.

(ix) Photoisomerization of 2-Methylcyclohepta-2,4-dienone

Compound 28 (250 mg) was irradiated in 50% acetic acid (30 ml) according to Method F. After 10-15 hours of irradiation the solution was added dropwise to a saturated solution of sodium bicarbonate (20 ml), extracted with ether (4x20 ml), and dried (M_gSO_4). Careful evaporation of the solvent at atmospheric pressure left an oil (200 mg) which was separated into its components on column C.

Compound 31: $^m/e$ 122 (100), $^m/e$ 107 (21), $^m/e$ 94 (67). Anal. Calcd for $C_8H_{10}O$:C, 78.64; H, 8.26, Found: C, 78.48; H, 8.50. The ir spectrum had prominent bands at 3040, 2960, 2935, 2865, 1730, 1452, 1066, 1048, 728 cm^{-1}, indicative of a saturated ketone. The pmr spectrum, Table 12 and Figure 40, displayed the characteristic

AB pattern for the non-conjugated vinyl hydrogens, $J = 2.7$ Hz. The sharp singlet at τ 8.85 was assigned to the C_1 methyl group. In this position, coupling to other protons would be negligible. A broad multiplet at τ 6.97 was assigned to the C_5 bridgehead hydrogen. The high field region was complicated and decoupling experiments could not significantly simplify the situation. Compound <u>32</u>: $^m/e$ 122 (100), 107 (30), 94 (71). <u>Anal</u>: Calcd for $C_8H_{10}O$: C, 78.64; H, 8.26; Found: C, 78.68; H, 8.49. The ir, with bands at 3040, 2940, 2878, 1730, 1652, 1454, 1160, 780 cm^{-1}, suggested a non-conjugated ketone. As in the pmr spectrum of <u>8</u>, a broad singlet for that of <u>32</u> at τ 4.37 corresponding to one proton was assigned to the C_7 position. It was shown by double irradiation experiments to be coupled to a methyl group, $J = 1.5$ Hz, whose position at τ 8.27 also suggested a vinyl methyl. The chemical shift was very close to that of <u>8</u> at τ 8.18. Two broad multiplets were assigned to the C_1 and C_5 bridgeheads. Decoupling both the methyl and vinyl protons sharpened these peaks somewhat but it was obvious that they were further coupled. The high field region was extremely complex and little information could be obtained. <u>Compound 33</u>: $^m/e$ 122 (8), 107 (4), 94 (100). <u>Anal</u>. Calcd for $C_8H_{10}O$: C, 78.64; H, 8.26; Found: C, 78.86, H, 8.29. The ir spectrum had bands at 3080, 3030, 2970, 1775, 1305, 1262, 1100, and 1028 cm^{-1} which suggested an unsaturated carbonyl group in a strained ring. Very similar absorption bands were found for authentic 30 and 9. The pmr spectrum, although complicated, was simplified by double irradiation experiments. Two vinyls were found at τ 3.50 and τ 3.70 as an AB quartet, J = 6.0 Hz, further split by the bridgehead at τ 7.27, $J_{2,4}$ = 1.8 Hz and $J_{3,4}$ = 3.3 Hz. Irradiation of the bridgehead removed this secondary coupling to both H_2 and H_3. A sharp singlet at τ 8.80 was assigned to the bridgehead methyl.

(x) Control Experiments for (viii) and (ix)

(a) Irradiation of 1-Methylbicyclo[3.2.0]hept-6-en-2-one

Compound 31 (25 mg) in 50% acetic acid (3 ml) was irradiated for 5 hrs at 350 nm. Working-up the reaction as above gave a clear oil (22 mg) which glpc analysis, column D, showed that it consisted of 31 (57%) and 32 (43%). No other products were detected (1-2% limit).

(b) Irradiation of 29 and 30

This experiment was performed essentially as above, on 29 and 30 in separate runs. Analysis showed no reaction products, only starting material.

(c) Product Distribution as a Function of Irradiation Time

Although only one product from 27 and three from 28 were isolated in preparative scale runs, there existed the danger that products formed early in the reaction could undergo isomerization and decomposition due to prolonged irradiation. To test for this both 27 and 28 (100 mg) were separately irradiated in 50% acetic as above and aliquots were withdrawn after various reaction times from 5% to completion. Glpc analysis, column D, of the oil recovered from these aliquots showed no other products being formed during the course of the reactions. In preparative scale experiments, 28 was only 90-95% pure, the other 5-10% being 7-methylcyclohepta-2,4-dienone. "Impurities" shown to have arisen from photoreaction of this contaminant were observed in these runs.

(d) Retention Times of Bicyclo[3.2.0]hept-5-en-3-one and Bicyclo[2.2.1]hept-5-en-2-one on Column D

At 90° C the title compounds had retention times of 8 and 12 minutes respectively. Compounds 29 and 30 had retention times of 10 and 9 minutes respectively under these conditions. A mixture of all four ketones was easily separated using column D.

(xi) Irradiation of Protonated Cyclohepta-2,4-dienone

These experiments were carried out as in the case of protonated eucarvone ($T > -65°$, $\lambda > 370$ nm). The progress of the reaction was followed by running pmr spectra of the acid solution at various times. Only one product was formed during the course of the irradiations (40 min) and prolonged photolysis of it under these conditions demonstrated its photostability. The acid solution of the product was quenched (Method D) to give an oil whose ir spectrum in CCl_4 and glpc retention time (column D) was identical to 30 obtained from Dr. J. Warkentin.

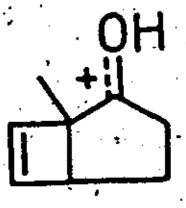
(xii) Irradiation of Protonated 2-Methylcyclohepta-2,4-dienone

These irradiations were conducted as above on samples of 28 (15-20 mg) in FSO_3H (0.4 ml) at $\lambda > 370$ nm and $T > -55°$. Isomerization of 28H took a much longer time than did that of 6H or 27H and normally the acid solutions were quenched after 30-40% reaction. In only several cases were the reactions taken to completion (6-7 hrs). The spectra of the product showed one cation, whose pmr were identical to that obtained from the protonation of 33. Compound 33 was obtained from <u>28</u> as described previously. For those reactions quenched (Method D), after shorter irradiation times, glpc analysis of the oil showed only <u>28</u> and <u>33</u>.

(xiii) Control Experiments for (xi) and (xii)

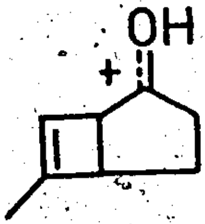
(a) Thermal Stability of 31H

This experiment was run to make certain <u>31H</u> (or a possible reaction product thereof) could have been detected if formed. Solution of <u>31</u> (15-20 mg) in 0.5 ml of $SO_2ClF:FSO_3H$ (2:1) at -110° (Method B) gave a cation whose pmr at -65° was consistent with <u>31H</u>. At <u>ca</u>. 40° this cation rearranged exclusively to a product which on the basis of the pmr was <u>32H</u>. Such a reaction is analogous to that reported in this thesis for the conversion of <u>7H</u> to <u>8H</u>. At -30°, <u>32H</u> was stable for 1 hour, however it underwent a rapid reaction at -15° to a species which was not identified. It was sufficiently clear that either <u>31H</u> or <u>32H</u> could have been readily detected in these experiments if formed.



<u>31H</u>

Vinyls	<u>2H</u>	τ4.22, 4.36
Bridgehead	<u>1H</u>	τ6.85
Other	<u>4H</u>	τ7.7
Methyl	3H	τ8.12



<u>32H</u>

Vinyl	τ <u>1H</u>	4.33
Bridgehead	τ <u>2H</u>	6.80, 6.89
Other	τ <u>4H</u>	7.41
Methyl	τ <u>3H</u>	8.31

(b) Thermal Stability of 30H

Compound 30 (25 mg) was protonated at -78° in FSO_3H (0.4 ml). At -45°, no change in the pmr spectrum of 30H took place after one hour. However when heated to ca. 0° very rapid decomposition took place as evidenced by the disappearance of the pmr signals of 30H. This result is in complete agreement with that reported earlier for 30H.[122]

(xiv) Thermal Isomerization of 47

Compound 47 (1 g) was distilled under vacuum through a 40-cm glass tube kept at a temperature greater than 200° with a Haskins Electric Furnace. The product (0.85 g) was collected in a trap at -78°. Glpc analysis showed that the oil contained 45% 47 and 55% 27. Pure samples of 27 were obtained by repeated glpc, column A. Obtained as such from 47, 27 had spectra identical with those previously reported.[98,105]

(xv) Protonation of 47 and 48

Most of the studies of 47H and 48H were examined by pmr. In general, FSO_3H solutions of 47H and 48H were prepared by Method A whereas H_2SO_4 solutions were made up by Method C.

(xvi) Thermal Isomerization of the Cations

All isomerizations were followed by monitoring the appropriate changes in the pmr spectra at the various temperatures indicated. Thermal stabilities of 27H, 28H and 49H were investigated by heating the acid solutions sealed in pmr tubes at +50° for several hours. Isomerization products were characterized by their pmr spectra in acid and from the spectral properties of the oils recovered upon quenching (Methods D and E). In aqueous sulphuric acids the reactions were complete in *ca.* 20 min, and quenching (Method E) at this stage gave reasonable yields of products (75-90%). On standing in the H_2SO_4-H_2O mixtures, decomposition of the products occurred (50% loss in 24 hrs).

(xvii) Kinetic Studies of 47H and 48H

These studies were performed on 4% (wt/wt) of the ketones in FSO_3H or FSO_3H-SbF_5 using dioxane as an internal standard. Since the rates were found to vary with the purity of FSO_3H, all rate studies were run using the same batch of doubly distilled FSO_3H. Solutions of the cations were kept in pmr tubes in an ice-water bath maintained at 0°. At appropriate time intervals the isomerizations were stopped by cooling to -78° and the extent of the reaction determined by integration of a pmr signal at -30°.

Reactions were followed to 90% completion and the rates evaluated as described in Method H.

(xviii) Thermal Isomerization of 47H

Compound 47 (30 mg) was protonated in FSO$_3$H (0.4 ml) at -78°. It was warmed up to 0° and allowed to isomerize. After several hours, no 47H remained as judged by pmr in FSO$_3$H at +37° (1% limit). The acid solution of 27H was quenched according to Methods D and E. Glpc analysis, column D, at 80° C, showed only 0.5% 47.

(xix) Thermal Isomerization of 48H

Compound 48 (35 mg) was protonated in FSO$_3$H (0.5 ml) at -78°. Thermal isomerization at 0° led to the complete disappearance of those peaks in the pmr spectrum attributable to 48H. The resultant solution displayed a pmr spectrum which featured a vinyl region similar to that of 27H and two methyl peaks at τ 7.74 and τ 8.59 in a 1:2 ratio respectively. The former was a singlet and the latter a doublet, J = 7.0 Hz. Quenching the solution (Method D) gave an oil, which had a strong absorption in the ir at 1650-1655 cm^{-1} and a uv max at 300 nm, log ϵ = 3.8-3.9. Glpc analysis, column D, 85°, showed two peaks at retention times of 14 and 16 minutes in the approximate ratio of 2:1. Repeated preparative glpc gave reasonably pure quantities (10-20mg) of

49 and 28 respectively. Compound 28. Pmr (Table 14); uv (Table 13); ir (thin film) 3040, 2980, 1653, 1435, 1360, 1228, 705 cm^{-1}. Compound 49. ir (thin film) 3035, 2980, 1655, 1435, 1360, 675 cm^{-1}. uv max (MeOH) 295 nm, log ϵ = 3.8.

PART 7. BIBLIOGRAPHY

REFERENCES

1. (a) J. G. Calvert and J. N. Pitts, "Photochemistry", J. Wiley and Sons Ltd., New York, (1966);
   (b) R. O. Kan, "Organic Photochemistry", McGraw-Hill, Inc., New York, (1966);
   (c) N. J. Turro, "Molecular Photochemistry", W. Benjamin, Inc., New York (1965);
   (d) J. N. Pitts, F. Wilkinson, and G. S. Hammond, Advan. Photochem., 1, 1 (1963).
2. J. W. Sidman, J. Chem. Phys., 27, 429 (1957).
3. (a) E. M. Kosower, J. Amer. Chem. Soc., 80, 3261 (1958);
   (b) E. M. Kosower and D. C. Remy, Tetrahedron, 281 (1959).
4. (a) A. A. Lamola, J. Chem. Phys., 47, 4810 (1967); see also (b) P. A. Leermakers, H. T. Thomas, L. D. Weis and F. C. James, J. Amer. Chem. Soc., 88, 5075 (1966); P. A. Leermakers, ibid., 90, 2246 (1968).
5. R. L. Cargill, W. A. Brady, D. M. Pond, A. B. Sears, J. Saltiel, and J. Winterale, Mol. Photochem., 3, 123 (1972).
6. G. Marsh, D. R. Kearns, and M. Fisch, J. Amer. Chem. Soc., 92, 2252 (1970); D. Bellus, D. R. Kearns, and K. Schaffner, Helv. Chim. Acta., 52, 971 (1969); G. Marsh,

D.R. Kearns, and K. Schaffner, ibid., 51, 1890 (1968); ibid., J. Chem. Phys., 49, 3316 (1968).

7. (a) J. Griffiths and H. Hart, J. Amer. Chem. Soc., 90, 3297 (1968); ibid., 90, 5296 (1968);
(b) H. Hart, P. M. Collins, and A. J. Waring, ibid., 88, 1005 (1968); for a review see G. Quinkert, Angew. Chem. Internat. Ed., 11, 1072 (1972).

8. W. G. Dauben, W. A. Spitzer, and M. S. Kellog, J. Amer. Chem. Soc., 93, 3674 (1971); D. I. Schuster and D. F. Brizzolara, ibid., 92, 4357 (1970).

9. G. Porter and P. Suppan, Pure. Appl. Chem., 9, 499 (1964).

10. H. E. Zimmerman, Advan. Photochem., 1, 183 (1963).

11. G. Marsh, D. R. Kearns, K. Schaffner, J. Amer. Chem. Soc., 93, 3129 (1971).

12. S. P. Pappas, R. D. Zehr, J. E. Alexander, and G. L. Long, J. Chem. Soc., Chem. Commun., 318 (1971); J. Jortner, S. P. Rice, and R. M. Hochstrasser, Advan. Photochem., 7, 149 (1969).

13. D. H. R. Barton, P. deMayo, and M. Shafiq, J. Chem. Soc., 140 (1958); ibid., 929 (1957).

14. S. W. Benson, J. Chem. Ed., 42, 502 (1965); H. M. Frey and R. Walsh, Chem. Rev., 69, 103 (1969); S. W. Benson, "Thermochemical Kinetics", Wiley and Sons, Inc., New York (1968).

15. E. Vogel, Justus Liebigs Ann. Chem., 615, 14 (1958).

16. R. Criegee, D. Seeback, R. E. Winter, B. Barratzen, and H. A. Brune, Chem. Ber., 98, 2339 (1965).

17. H. M. Frey, D. Dickens, and R. F. Skinner, Trans. Far. Soc., 65, 441, 448, 453 (1969).

18. J. E. Baldwin, A. H. Andrist, and R. K. Pinschmidt, Accounts Chem. Res., 5, 402 (1973); J. A. Berson, ibid., 5, 406 (1973).

19. R. B. Woodward and R. Hoffmann, "The Conservation of Orbital Symmetry", Verlag Chemie, Weinheim/Bergstr., (1970).

20. N. D. Epiotis, J. Amer. Chem. Soc., 94, 1941, 1946 (1972).

21. R. Srinivasan, Advan. Photochem., 1, 83 (1963).

22. J. Saltiel, K. R. Neubergen, and M. Wrighton, J. Amer. Chem. Soc., 91, 3658 (1969).

23. I. H. Kochevar and P. J. Wagner, ibid., 92, 5742 (1970).

24. O. L. Chapman, Advan. Photochem., 1, 353 (1963).

25. H. E. Zimmerman and D. I. Schuster, J. Amer. Chem. Soc., 83, 4486 (1961); ibid., 84, 4527 (1962).

26. P. E. Freeman and W. Klemperer, J. Chem. Phys., 45, 52, 58 (1966), and references therein.

27. (a) H. E. Zimmerman and J. S. Swenton, J. Amer. Chem. Soc., 89, 906 (1967); H. E. Zimmerman and J. O. Grunewald, ibid., 89, 5163 (1967); H. E. Zimmerman, D. S. Crumine, D. Dopp, and P. S. Huyffer, ibid., 91, 434 (1969); H. E. Zimmerman and G. A. Epling, ibid.,

94, 7806 (1972);

(b) H. E. Zimmerman, R. W. Binkley, J. J. McCullough, and G. A. Zimmerman, ibid., 89, 6589 (1967).

28. H. E. Zimmerman, R. C. Hahn, H. Morrison and M. C. Wani, ibid., 87, 1138 (1965); H. E. Zimmerman, R. D. Rieke, and J. Scheffer, ibid., 89, 2033 (1967); and references therein.

29. (a) G. S. Hammond and N. J. Turro, Science, 142, 1541 (1963);

(b) J. S. Swenton, E. Saurborn, R. Srinivasan, and F. I. Sonntag, J. Amer. Chem. Soc., 90, 2990 (1968);

(c) D. I. Schuster and D. J. Patel, ibid., 90, 5145 (1968); D. I. Schuster and C. J. Polowczyk, ibid., 4502 (1964);

(d) G. A. Taylor, J. Chem. Soc., Chem. Commun., 896 (1967), for a reply to this paper see H. E. Zimmerman, ibid., 174 (1968).

30. P. J. Wagner and G. S. Hammond, Advan. Photochem., 5, 21 (1967).

31. (a) E. C. Freidlich, J. Org. Chem., 33, 413 (1968);

(b) L. Eberson and S. Winstein, J. Amer. Chem. Soc., 87, 3506 (1965);

(c) G. A. Olah, Y. Halpern, Y. K. Mo, and G. Liang, ibid., 94, 3554 (1972).

32. E. M. Arnett, Progr. Phys. Org. Chem., 1, 223 (1963).

33. P. A. Leermakers, G. W. Byers, and R. Rusakowicz, J. Amer. Chem. Soc., 93, 3263 (1971).

34. R. F. Childs, Paper presented at the Joint Conference of C. I. C. and A. C. S., Toronto, Canada, May 1970.

35. (a) R. F. Childs and S. Winstein, J. Amer. Chem. Soc., 90, 7146 (1968);
    (b) E. E. van Tamelen, T. M. Cole, R. Greely, H. Schumacher, ibid., 90, 1372 (1968);
    (c) B. D. Parrington, MSc. Thesis, McMaster University, November (1971).

36. H. Meerwein, G. Hinz, P. Hoffmann, E. Kronig, and E. Pfeil, J. Prakt Chem., 147, 257 (1937).

37. G. A. Olah, Angew. Chem. Internat. Ed., 12, 173 (1973).

38. R. J. Gillespie and T. Birchall, Can. J. Chem., 41, 148 2642 (1963); R. J. Gillespie, Accounts Chem. Res., 1, 202 (1968).

39. B. Parrington and R. F. Childs, J. Chem. Soc., Chem. Commun., 1581 (1970).

40. R. Hoffmann, J. Amer. Chem. Soc., 90, 1475 (1968).

41. H. E. Zimmerman, R. Keese, J. Nasielski, and J. S. Swenton, ibid., 88, 4895 (1966).

42. G. Büchi and E. M. Burgess, ibid., 82, 4333 (1960).

43. O. L. Chapman and D. J. Pasto, ibid., 82, 3642 (1960).

44. D. I. Schuster and D. H. Sussman, Tetrahedron Lett., 1657 (1970).

45. J. J. Hurst and G. H. Whitham, J. Chem. Soc., 710 (1963).

46. (a) Th. Forster, Z. Electrochem. Angew. Physik. Chem., 54, 42 (1950);
(b) A. Weller and W. Urban, Angew. Chem., 60, 336 (1954).
(c) G. Jackson and G. Porter, Proc. Roy Soc., A, 200, 13 (1961).

47. (a) A. Weller, Progr. Reaction Kinetics, 1, 187 (1961);
(b) E. Vander Donckt and G. Porter, Trans. Far. Soc., 64, 3215 (1968);
(c) A. C. Hopkinson and P. Wyatt, J. Chem. Soc., B, 1333 (1967);
(d) E. Vander Donckt, Progr. Reaction Kinetics, 5, 273 (1970).

48. (a) P. J. Kropp, "Organic Photochemistry", O. L. Chapman, Ed., M. Dekker Inc., New York (1967);
(b) K. Schaffner, Advan. Photochem., 4, 81 (1967).

49. For more recent examples, see:
(a) D. Bryce-Smith and G. B. Cox, J. Chem. Soc., Chem. Commun., 914, 915 (1971);
(b) D. I. Schuster and V. Y. Abraitys, ibid., 419 (1969);
(c) R. Hurley and A. C. Testa, J. Amer. Chem. Soc., 89, 6917 (1967); P. J. Kropp, ibid., 91, 5783 (1969);
(d) H. Nozaki, M. Kuritor, and R. Noyori, Tetrahedron

Lett., 3635 (1968).

50. D. I. Schuster, M. J. Nash, and M. L. Kantor, ibid., 1375 (1964).

51. H. Hart and T. Takino, J. Chem. Soc., Chem. Commun., 450 (1970).

52. H. Hart and T. Takino, J. Amer. Chem. Soc., 93, 720 (1971).

53. A. Cornelis, personal communication to this author, July, 1971. A. Cornelis and P. Laszlo, Org. Mag. Res., 5, 95 (1973).

54. J. B. Stothers, Quart. Rev., (London) 151 (1965); L. D. McKeever, R. Waack, M. A. Doran, and E. B. Baker, J. Amer. Chem. Soc., 91, 1057 (1969); cf. 31(c).

55. V. P. Vitullo, J. Org. Chem., 34, 224 (1969); K. L. Cook, M. J. Hughes, and A. J. Waring, J. Chem. Soc., Perkin II, 1506 (1972).

56. J. D. Holmes and R. Pettit, J. Amer. Chem. Soc., 85, 2531 (1963).

57. R. J. Gillespie and T. E. Peel, Advan. Phys. Org. Chem., 9, 1 (1971).

58. G. A. Olah, C. U. Pittman, Jr., and M. C. R. Symons, in "Carbonium Ions", Vol 1, G. A. Olah and P. von R. Schleyer Ed., Wiley-Interscience, N. Y. (1970) pp153.

59. A. Zabza and H. Kvczynski, Rocz. Chem., 40, 463 (1966).

60. L. A. Paquette and O. Cox, J. Amer. Chem. Soc., 89, 5633 (1967).

61. R. M. Silverstein and G. C. Bassler, "Spectrometric Identification of Organic Compounds", J. Wiley and Sons, N. Y. (1967) pp 160.

62. R. F. Childs and V. Taguchi, J. Chem. Soc., Chem. Commun., 695 (1970).

63. K. E. Hine and R. F. Childs, Paper Presented at the 56th Chemical Conference of the C. I. C., Montreal, June, 1973. Abstract No. 215.

64. E. M. Kosower, "An Introduction to Physical Organic Chemistry", J. Wiley and Sons, N. Y. (1968) pp 306-308.

65. J. R. Dyer, "Applications of Absorption Spectroscopy", Prentice Hall, Inc., N. J. (1965) pp. 80-81.

66. L. M. Jackman and G. Sternhell, "Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry", Pergamon Press, New York, (1966).

67. S. C. Lewis and G. H. Whitham, J. Chem. Soc., C, 274 (1967).

68. O. L. Chapman, D. J. Pasto, G. W. Borden, and A. A. Griswold, J. Amer. Chem. Soc., 84, 1220 (1962).

69. O. L. Chapman and E. D. Hoganson, ibid., 86, 498 (1964).

70. G. A. Olah, J. Sommer, and E. Namanworth, ibid., 89, 3576 (1967).

71. R. K. Lusgarten, M. Brookhart, and S. Winstein, ibid., 94, 2347 (1972).

72. S. Winstein, Quart. Rev., Chem. Soc., 23, 141 (1969).

73. M. Brookhart, A. Diaz, and S. Winstein, J. Amer. Chem. Soc., 90, 3135 (1968).

74. C. H. Nicholls and P. A. Leermakers, Advan. Photochem., 8, 315 (1971).

75. P. J. Wagner and G. S. Hammond, J. Amer. Chem. Soc., 88, 1245 (1966); D. I. Schuster and I. S. Krull, Mol. Photochem., 1, 107 (1969); H. E. Zimmerman and T. W. Flechtner, J. Amer. Chem. Soc., 92, 6931 (1970).

76. F. Wilkinson, Advan. Photochem., 3, 241 (1964).

77. K. E. Hine and R. F. Childs, J. Amer. Chem. Soc., 93, 2323 (1971).

78. K. E. Hine and R. F. Childs, J. Chem. Soc., Chem. Commun., 144 (1972).

79. K. E. Hine and R. F. Childs, J. Amer. Chem. Soc., 95, 3289 (1973).

80. P. R. Story and S. R. Fahrenholtz, J. Amer. Chem. Soc., 87, 1623 (1965).

81. K. E. Hine and R. F. Childs, J. Chem. Soc., Chem. Commun., 145 (1972).

82. D. I. Schuster and M. A. Tainsky, Mol. Photochem., 4, 437 (1972).

83. H. G. Richey and R. K. Lustgarten, J. Amer. Chem. Soc.,

88, 3136 (1966).

84. (a) T. S. Sorensen in "Carbonium Ions", Vol. 2, Ed. by G. A. Olah and P. von R. Schleyer, Wiley-Interscience, N. Y. (1970) pp. 807-835;
(b) T. S. Sorensen, J. Amer. Chem. Soc., 87, 5075 (1965).

85. R. Noyori, Y. Ohnishi, and M. Kato, ibid., 94, 5105 ((1972).

86. H. Hart and A. F. Naples, ibid., 94, 3246 (1972).

87. P. E. Eaton and K. Lin, ibid., 87, 2052 (1965); E. J. Corey, M. Tada, R. LeMahieu, and L. Libit , ibid., 87, 2051 (1965).

88. A. Devaquet, ibid., 94, 5160 (1972).

89. R. F. Childs and B. Morrisey, unpublished results; B. Morrisey, BSc. Thesis, McMaster University, April (1973).

90. R. F. Childs, F. A. Hung, and K. E. Hine, Paper presented at the 56th Chemical Conference of the C. I. C., Montreal, June 1973. Abstract no. 208.

91. O. L. Chapman, T. A. Rettig, A. A. Griswold, A. I. Dutton and P. Fitton, Tetrahedron Lett., 2049 (1963).

92. D. M. Brouwer and H. Hogeveen, Recl. Trav. Chim. Pays-Bas, 89, 271 (1970).

93. R. F. Childs and B. Parrington, J. Chem. Soc., Chem.

Commun., 1540 (1970); E. D. Owen and D. M. Allen, J. Chem. Soc., Perkin II, 95 (1973); D. Bethell and P. N. Clare, ibid., 1464 (1972); and references therein.

94. P. J. Kropp and W. F. Erman, J. Amer. Chem. Soc., 85, 2456 (1963); H. Hart and D. W. Swatton, ibid., 89, 1874 (1967); J. K. Crandall and R. P. Haseltine, ibid., 90, 6251 (1968); D. I. Schuster and K. C. Liu, ibid., 93, 6711 (1971); D. Caine, P. F. Brake, J. F. Debardelen, and J. B. Dawson, J. Org. Chem., 38, 967 (1973).

95. H. E. Zimmerman and W. R. Elger, J. Amer. Chem. Soc., 91, 887 (1969).

96. E. E. van Tamelen and G. T. Hildahl, ibid., 78, 4405 (1956).

97. O. L. Chapman, D. J. Pasto, and A. A. Griswold, ibid., 84, 1213 (1962).

98. A. P. terBorg and H. Kloosterziel, Recl. Trav. Chim. Pays-Bas, 82, 1189 (1963).

99. (a) T. Nozoe, T. Mukai, and T. Tezuka, Bull. Chem. Soc. Jap., 34, 619 (1961);

(b) cf. A. P. terBorg, R. van Helden, and A. F. Bickel, Recl. Trav. Chim. Pays-Bas, 81, 591 (1962).

100. H. Hogeveen, ibid., 87, 1299 (1968).

101. (a) G. A. Olah and M. Calin, J. Amer. Chem. Soc., 90, 938 (1968) ; (b) D. S. Noyce and M. Evett, J. Org. Chem., 37 , 394 (1972).

102. G. M. Badger, "Aromatic Character and Aromaticity", Cambridge University Press, Cambridge, U.K. (1969) pp. 71.

103. N. C. Deno, H. G. Richey Jr., J. S. Liu, D. N. Lincoln and J. O. Turner, J. Amer. Chem. Soc., 87, 4533 (1965).

104. N. C. Deno, Progr. Phys. Org. Chem., 2, 129 (1964).

105. D. J. Bertelli, T. G. Andrews and P. O. Crews, J. Amer. Chem. Soc., 91, 5286 (1969).

106. E. Garbisch, J. Org. Chem., 30, 2109 (1965).

107. R. F. Childs, J. Chem. Soc., Chem. Commun., 946 (1969).

108. N. C. Deno in "Carbonium Ions", Vol 2. G. A. Olah and P. v. R. Schleyer, Ed., Wiley-Interscience, N. Y. (1970), pp. 790-791.

109. W. E. Parham, R. W. Soeder and R. M. Dodson, J. Amer. Chem. Soc., 84, 1755 (1962).

110. R. A. Robinson and R. H. Stokes, "Electrolyric Solutions", 2nd ed., Academic Press Inc., New York, N. Y., 1959; H. T. S. Britton, "Hydrogen Ions", Vol. 1, D. van Nostrand Co., Inc., New York, N. Y., 1956.

111. E. J. Corey and H. J. Burke, J. Amer. Chem. Soc., 78, 174 (1956).

112. A. A. Bothner-By and E. Moser, ibid., 90, 2347 (1968).

113. P. Radlick, J. Org. Chem., 29, 960 (1964).

114. D. I. Schuster, B. R. Sckolnick and F. T. H. Lee, J. Amer. Chem. Soc., 90, 1300 (1968).

115. S. J. Cristol and P. K. Freeman, ibid., 83, 4427 (1961).

116. D. I. Schuster, M. Axelrod and J. Auerbach, Tetrahedron Lett., 1911 (1963).

117. P. Gassman and P. G. Pape, J. Org. Chem., 29, 160 (1964).

118. H. Hogeveen, ~~C. F.~~ Roobeek, and H. C. Volger, Tetrahedron Lett., 221 (1972).

119. R. Srinivasan, J. Amer. Chem. Soc., 81, 5541 (1959).

120. B. Ramachandran, private communication.

121. L. A. Paquette, J. H. Barrett, R. P. Spitz, and R. Pitcher, J. Amer. Chem. Soc., 87, 3417 (1965); L. A. Paquette and J. H. Barrett, ibid., 88, 1718 (1966); see also Y. L. Chow, J. Streith, and G. Tourend, Org. Mag. Res., 5, 155 (1973).

122. M. Brookhart, PhD. Thesis, U. C. L. A., 1968.