SOME REARRANGEMENTS OF CYCLOBUTENES AND CYCLOBUTYLIDENES

A Thesis submitted to the
University of Southampton
for the degree of
DOCTOR OF PHILOSOPHY

by

Michael James Curry

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To my wife.

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ABSTRACT

FACULTY OF SCIENCE

CHEMISTRY

Doctor of Philosophy

SOME REARRANGEMENTS OF CYCLOBUTENES AND CYCLOBUTYLIDENES

by Michael James Curry

The work presented in this thesis is concerned with certain rearrangements of some four-membered ring compounds, in particular cyclobutenes and cyclobutylidenes.

Cyclobutenes are well-known for their thermal rearrangements to 1,3-butadienes, via the conrotatory movement of the methylene groups. The 3,3-disubstituted cyclobutenes have available two possible directions of ring-opening, both conrotatory, such that Z and E-1,3-dienes are formed as products. 3-Ethyl-3-methylcyclobutene has been previously found to yield the thermodynamically less stable Z-1,3-diene as major product of the rearrangement. In this work, certain other 3-alkyl-3-methylcyclobutenes and 3-aryl-3-methylcyclobutenes have been shown also to yield more of the Z product (for alkyl = i-propyl and n-propyl and aryl = 4-methoxyphenyl). The steric and electronic effects of the substituents are important in deciding the stereochemical outcome of the isomerisation, and these factors are discussed though no firm conclusions can be reached.

For this study, a new synthesis of the 3,3-disubstituted cyclobutenes was developed. 2,2-Disubstituted cyclobutanones were prepared by reaction of cyclopropylidene diphenylsulphonium ylide with a suitable methyl ketone, and isomerisation of the intermediate spiro-epoxide without isolation.

Decomposition of the tosylhydrazones of the cyclobutanones with a two molar excess of methyl lithium afforded the cyclobutenes in isolated yields of greater than 70%.

The kinetics of isomerisation of 3-t-butyl-3-methylcyclobutene and 3-methyl-3-phenylcyclobutene have been measured, and the results compared to the data of previous work by Frey and by Brauman. The rate equations for these compounds were found to be:

$$k_{t\text{-butyl}} = 10^{14.13} \exp(-151.2 \times 10^3 J/RT) \quad s^{-1} \quad (158\text{-}200^{o})$$

$$k_{phenyl} = 10^{12.28} \exp(-124.5 \times 10^3 J/RT) \quad s^{-1} \quad (120\text{-}180^{o})$$

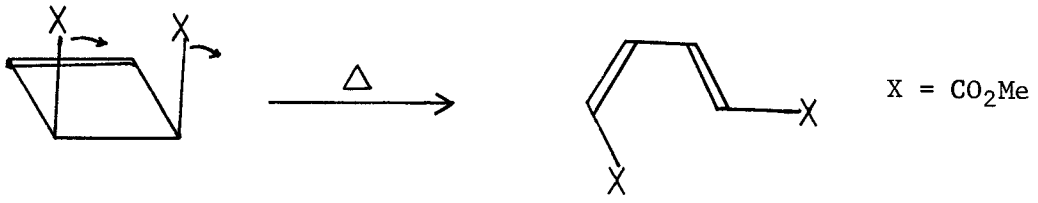
Cyclobutylidenes have been prepared by the decomposition of the sodium salts of the cyclobutanone tosylhydrazones by pyrolysis under vacuum. The carbenes rearrange mainly to the more substituted methylenecyclopropanes, though further rearrangements have been found to occur. The effect of copper on these decompositions has been observed. It is found that yields are markedly increased, though further rearrangements to vinylcyclopropanes are facilitated by its presence.

CHAPTER 1

INTRODUCTION

The stereochemistry of the thermal ring-opening of a cyclobutene was first established in 1954 by Vogel,[1,2] who demonstrated that the pyrolysis of cis-3,4-dicarbomethoxycyclobutene (1) yielded solely (Z,E)-1,4-dicarbomethoxybuta-1,3-diene (2) via a conrotatory motion of the substituents, as shown in scheme 1.

Scheme 1

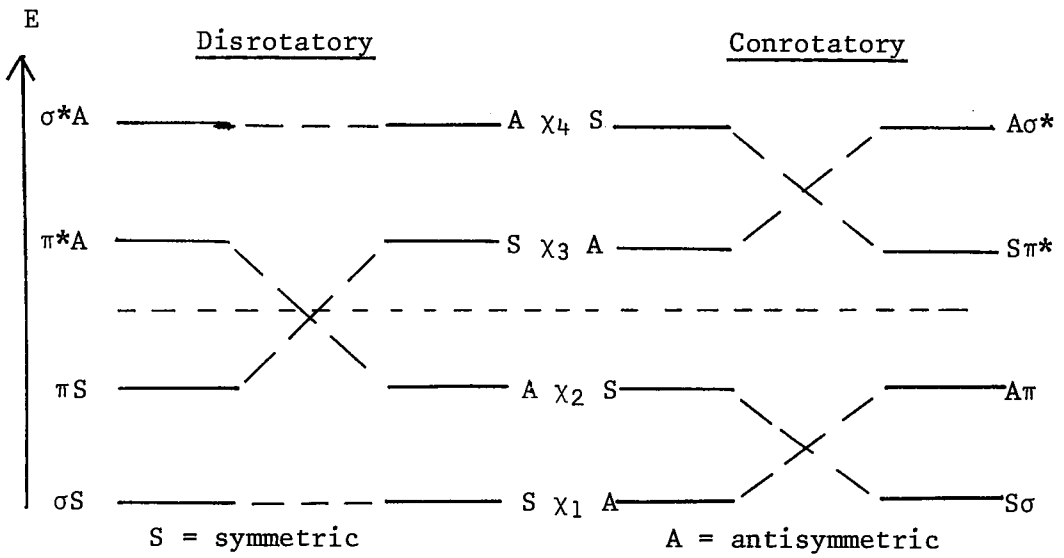


(1) (2)

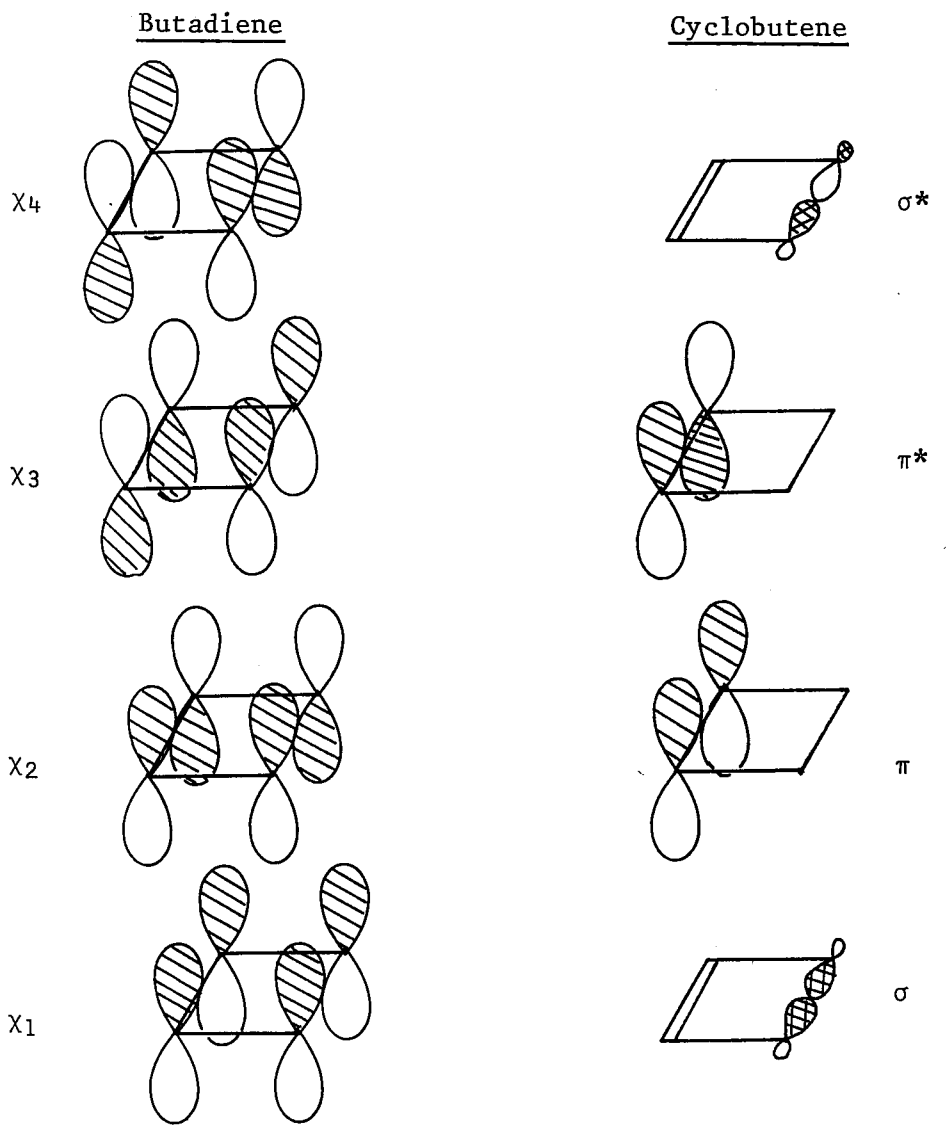
Woodward and Hoffmann[3] have recently explained the stereospecifity of this reaction by the use of orbital symmetry arguments and have concluded that orbital symmetry is conserved in concerted reactions. The construction of correlation diagrams for the change cyclobutene - s-cis-butadiene shows that the disrotatory mode of ring-opening, characterised by a plane of symmetry, correlates with an excited state of the product thus making that thermal reaction symmetry forbidden. Conversely, the conrotatory mode, which preserves a two-fold axis of symmetry during the ring-opening, is thermally allowed as illustrated in figure 1.

Figure 1

Correlation diagrams for the change cyclobutene - s-cis-butadiene



where the molecular orbitals used are as follows:



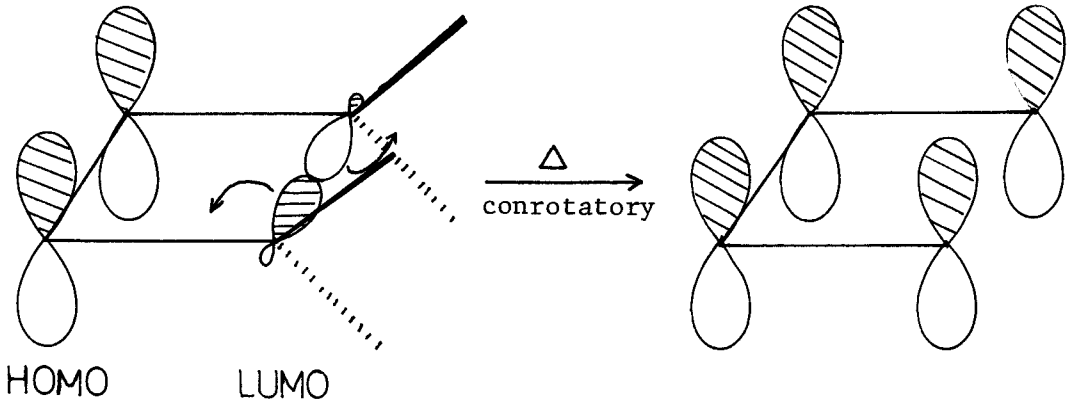
The arguments used in this type of approach are applicable only to cyclobutene itself since the effect of any substituent group is to destroy the total symmetry of the system. However, since substitution would not be expected to drastically change the mechanism of the reaction, the overriding factor in the treatment is the production of a high energy level transition state during the disrotatory opening, making that mode of ring-opening energetically unfavourable.

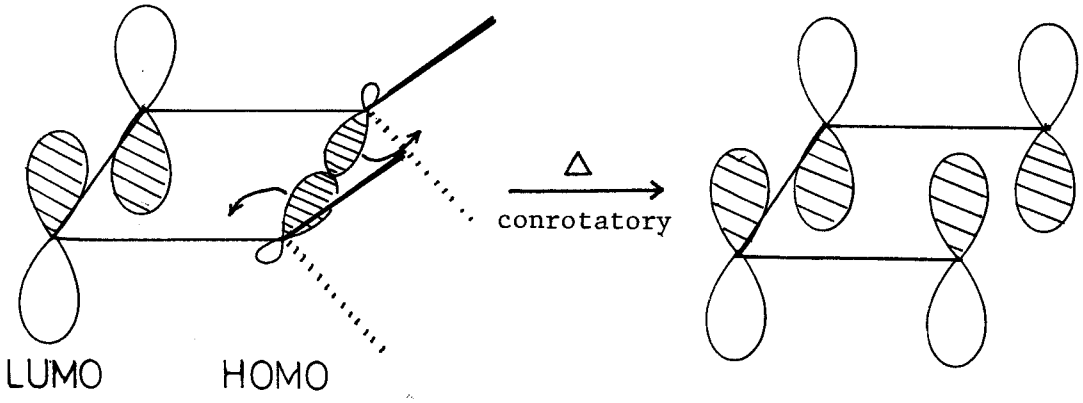
Another approach to this problem, not involving symmetry properties, was developed by Fukui,[4] which stressed the importance of the highest occupied and lowest unoccupied orbitals of the system. This frontier orbital treatment analyses the orbital interactions, between the highest occupied molecular orbitals (HOMO) and the lowest unoccupied molecular orbitals (LUMO), in determining the stereochemical path of a reaction and proposes that the reaction should proceed in the direction of maximum overlap between the HOMO and LUMO of the reacting species. This is represented for the cyclobutene isomerisation as shown in scheme 2.

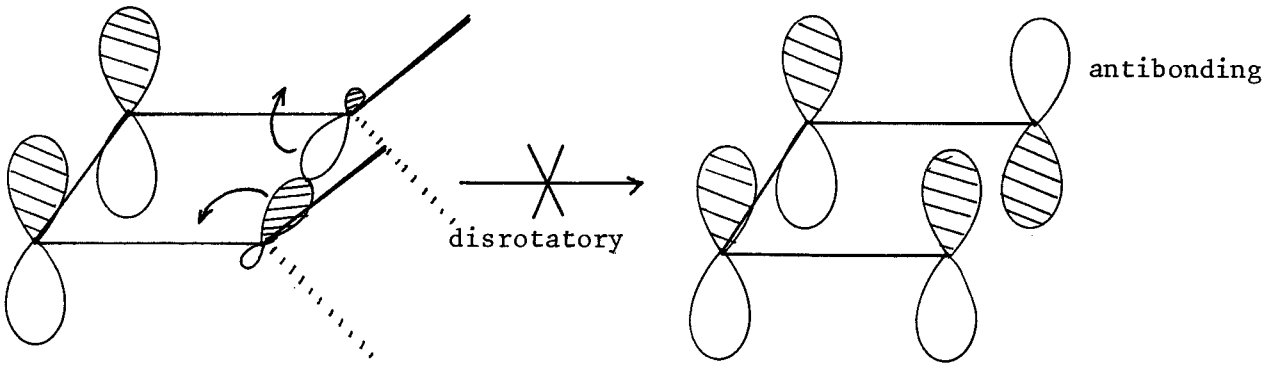
The region in which the HOMO-LUMO interaction is considered is taken as that which is crossed by the newly formed bonds. The only effect here of a substituent will be to affect the absolute energies of the HOMO and LUMO.

Although these methods successfully illustrated the correct mode of ring-opening, the actual mechanism of the change had not been analysed. Woodward and Hoffmann[3] assumed that the two methylene groups of cyclobutene rotated in unison (in a conrotatory manner) as the bond joining them was stretched and broken, in a smooth continuous process. However, recent "ab initio" calculations on the cyclobutene - s-cis-

Scheme 2


Δ
conrotatory
HOMO
LUMO

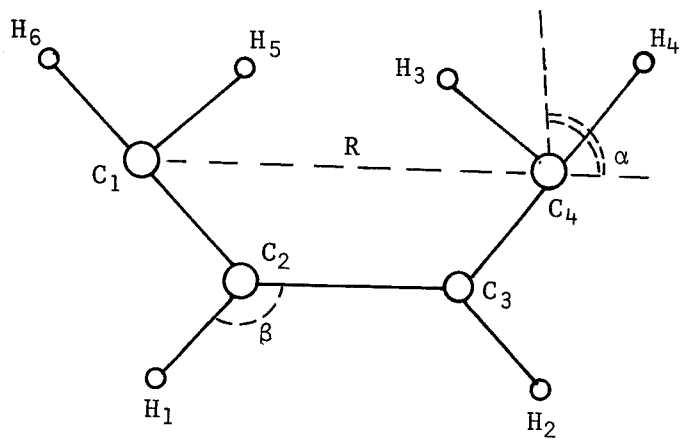

Δ
conrotatory
LUMO
HOMO


disrotatory
antibonding

butadiene transformation by Buenker, Peyerimhoff and Hsu[5] draw a rather different picture of the detailed mechanism. Several cross-sections through the potential energy surface of the transformation were analysed in detail in an attempt to determine the true reaction path (that of minimum energy) and to calculate the activation energy of the process.

Taking 24 degrees of freedom into account, simplifying assumptions were made about the symmetry maintained throughout the reaction thus reducing the number of independent parameters. A knowledge of the geometries of both cyclobutene and s-cis-butadiene enabled those parameters that remained unchanged to be eliminated. The parameters exhibiting the largest changes during the reaction were the out-of-plane rotation of the methylene groups, θ, and the carbon-carbon bond distance, R (Figure 2), and these were taken as the principal independent variables. Other significant changes taken into account included the other carbon-carbon bond distances and the angles α and β though these were not optimised so thoroughly.

Figure 2



The calculations showed that for every distance R, the lowest energy conformation had θ either equal to 0^{o} or 90^{o}, which could only be reasonably explained by rotation of the methylene groups entirely and only at a distance R' where the 0^{o} and 90^{o} conformations had equal energy. This process described an initial bond-stretching to a given distance R' (calculated to be about 60% of the distance between cyclobutene and s-cis-butadiene), at which point rotation of the methylene groups occurred followed by relaxation into the final product geometry.

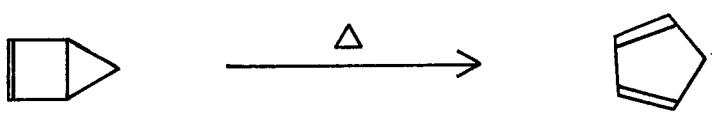
Variations of the angle θ between 0^{o} and 90^{o} in 15^{o} intervals at this distance R' enabled further calculations to show that the conrotatory mode of ring-opening was clearly favoured over the disrotatory mode. Configuration interaction (C.I) calculations gave an estimate of 57 k.joules $mol.^{-1}$ for the energy difference between the two modes. From these results the overall activation energy of the process was calculated to be in the order of 197 k.joules $mol.^{-1}$, said to be in reasonable agreement with the experimental value (136.0 k.joules $mol.^{-1}$).[6]

Similar work on the same system using the Complete Neglect of Differential Overlap (CNDO) type of calculations has been reported by Dewar.[7] Utilising the MINDO/2 method and taking the bond distance R as the only variable, the calculations pointed to the geometry of the reacting species changing steadily during the transformation, and gave a rather high estimate for the activation energy of 230 k.joules $mol.^{-1}$. However it is well recognised[8] that the MINDO/2 method overestimates the stability of small ring systems, and so its predictions on these systems can be regarded as rather inaccurate.

The conrotatory mode for the thermal ring-opening of cyclobutene has been shown to be energetically more favourable than the disrotatory mode, calculations giving an energy difference between the two modes of approximately 55 k.joules $mol.^{-1}$. Several approaches to the experimental determination of this energy difference (ΔE) have been made, in particular by Brauman[9] and Doorakian and Freedman,[10] with the results obtained being in the region of the calculated value.

Thus a study[11] of the gas-phase decomposition of bicyclo[2.1.0]pent-2-ene (3), by a non-allowed pathway to cyclopentadiene (4), scheme 3, and the use of thermochemical data enabled Brauman to estimate the value of ΔE at approximately 63 k.joules $mol.^{-1}$.

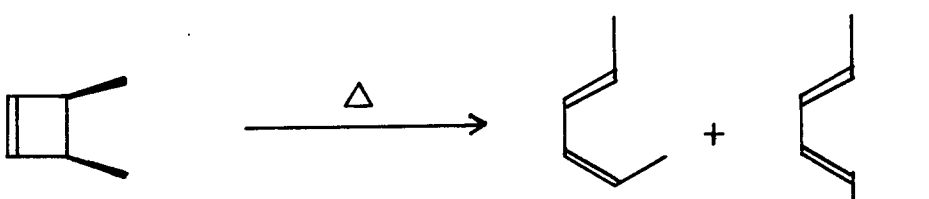
Scheme 3



(3) (4)

Another method[12] utilised by the same workers involved the analysis by gas-liquid chromatography (g.l.c.) of the non-allowed products of the pyrolysis at 280° of cis-3,4-dimethylcyclobutene[13] (5) (scheme 4).

Scheme 4

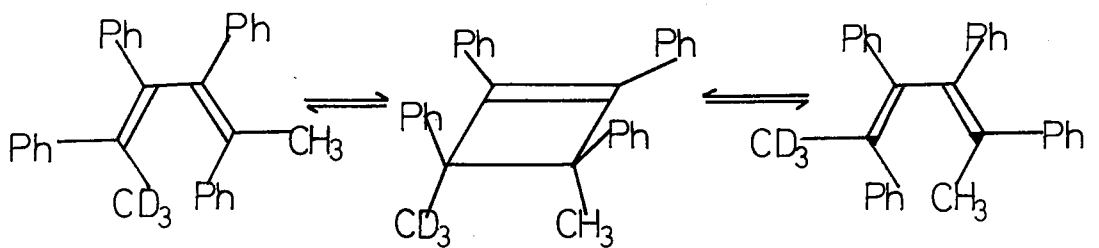


(5) (6) allowed (7) non-allowed

0.005% of (E,E)-hexa-2,4-diene (7) was detected, giving a ΔE value of greater than or equal to 63 k.joules $mol.^{-1}$.

Doorakian and Freedman[10] have studied the thermal isomerisation of the highly substituted cis-cyclobutene (8), (scheme 5).

Scheme 5



(Z,E) (9) (8) (E,Z) (10)

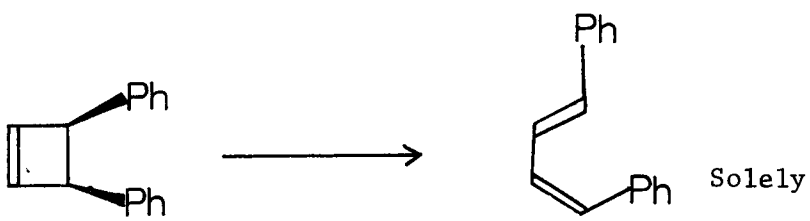
When the (Z,E) diene (9) was heated in solution above 110° the ratio of the isomers (Z,E), (9), and (E,Z), (10), became exactly 1:1, via the reversible formation of the intermediate cyclobutene (8) and its conrotatory opening. After heating this solution at 124° for 51 days in a sealed N.M.R. tube no (Z,Z) product (non-allowed) was observed, giving an estimated ΔE of 31 k.joules $mol.^{-1}$.[14]

It should be noted that the values of ΔE obtained from these experiments are a measure of the energy advantage associated with the orbital symmetry allowed pathway (conrotatory) for the ring-opening of various cyclobutenes, as opposed to some non-allowed pathway - not necessarily the disrotatory one. In many other apparently orbital symmetry controlled processes[9] the alternative pathway must logically involve fully bond-broken species or diradicals. For the cyclobutene isomerisation, however, it is not possible to say with any degree of

certainty whether the non-allowed pathway involves a diradical species or an orbital symmetry forbidden disrotatory path, a problem almost impossible to solve experimentally. Calculations[9] using thermochemical data estimate the energy of the formation of the diradical species from cyclobutene at about 197 k.joules $mol.^{-1}$, a difference of 63 k.joules $mol.^{-1}$ above the actual activation energy for its isomerisation. Since 63 k.joules $mol.^{-1}$ is also the estimate for the energy difference between the allowed and non-allowed pathways, this could indicate that the non-allowed species is the diradical.

Brauman[15] has attempted to stabilise the diradical species, if present, by appropriate substituents that might make this pathway more competitive with the allowed one. Cis-3,4-diphenylcyclobutene (11) was synthesised for this purpose, but the thermal reaction was found to be greater than 99% stereospecific (scheme 6), implying a predominantly concerted reaction.

Scheme 6



(11) (12)

Indeed, the cyclobutene (11) isomerised to the diene (12) at room temperature, and kinetic measurements revealed an activation energy for the process of 102.5 k.joules $mol.^{-1}$, a decrease of 42 k.joules $mol.^{-1}$ from cis-3,4-dimethylcyclobutene[16] (5).

The phenyl substituents obviously stabilised the concerted reaction as well as the radical species, which would have an estimated activation energy of only around 138 k.joules $mol.^{-1}$ (since it is to be expected that the stabilisation of the phenyl substituents will be greatest in the least stable system). The origin of this stabilisation, in the concerted reaction, by the phenyl substituents, of about 17-21 k.joules $mol.^{-1}$ each, was given by a delocalisation of the electron density associated with the termini of the π system onto the aromatic substituent, assuming the geometry of the overlap to be satisfactory.

To summarise, these experiments have shown that the thermal isomerisation of unconstrained cyclobutenes proceeds in a concerted, conrotatory manner without the intervention of disrotatory or diradical mechanisms.

The preceding theories and calculations, though carefully describing the course of the thermal ring-opening and giving reasonable estimates of the activation energy of the process for cyclobutene itself, provide no information about the dependence of the activation energy and reaction rate upon the nature and arrangement of substituents when incorporated into the cyclobutene system. This information has only been gained by the results of extensive series of kinetic measurements, performed mainly by Frey and his coworkers, on a wide range of substituted cyclobutenes.[17-35] These experiments have demanded extremely accurate monitoring of the isomerisation process, achieved by the use of N.M.R., U.V. or g.l.c. techniques where appropriate. In the majority of cases the isomerisations have been performed in the gas

phase though the highly substituted cyclobutenes have been suitable only for solution measurements. The reaction parameters have shown little or no dependence on the nature of the solvent employed[25] and hence allows these results to be compared directly to those of the gas phase reactions. In all instances the isomerisations have been found to be first order and unimolecular and to fit an Arrhenius plot of the form:

$$k = A \exp(-E_A/RT)$$

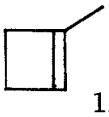
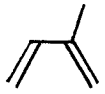
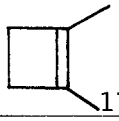
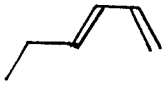
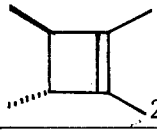
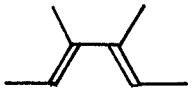
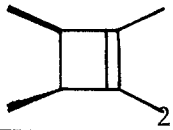
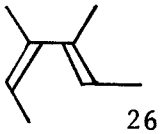
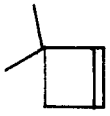
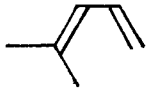
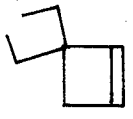
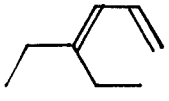
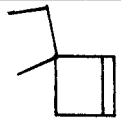
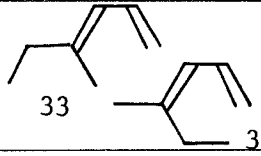
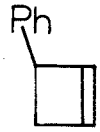
where k is the first order rate constant, A the pre-exponential factor and E_A the activation energy of the process.

The results of some of the measurements are shown in Table 1.

The low activation energy for the isomerisation of cyclobutene compared with that for the decomposition of cyclobutane of 261.6 k.joules $mol.^{-1}$ [37] has been accounted for by the rupture of only one bond in cyclobutene, and by this bond being already weakened by the increased strain in the ring due to the presence of the double bond. Furthermore, it has been argued that an alkyl substituent on the double bond by way of its electron donating properties should increase the length of this bond. This decreases the strain in the ring and hence increases the activation energy for the process. Thus an alkyl substituent at the 1-position increases the activation energy by about 10 k.joules $mol.^{-1}$, [17] and alkyl substituents at both the 1- and 2-positions increases the energy further still by a total of approximately 15 k.joules $mol.^{-1}$.

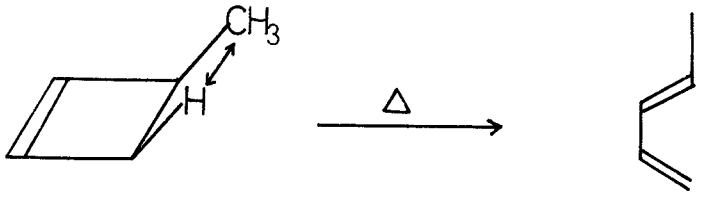
Conversely, substituents at the 3-position tend to decrease the activation energy of ring-opening, explained by a steric repulsion between the substituent and the adjacent C_4 hydrogens. This increases

Table 1: Activation Energies of Isomerisation of Some Cyclobutenes

Cyclobutene	E_A(k.joule mol^{-1})	$log_{10}A$	Product	Ref
 13	136.00	13.1	 14	6
 15	146.90	13.79	 16	17
 17	150.83	13.84	 18	18
 19	132.04	13.53	 20	19
 21	132.37	13.49	 22	35
 23	140.57	13.85	 24	24
 25	156.35	14.16	 26	24
 27	151.04	13.93	 28	26
 29	145.35	13.53	 30	28
 31	(a) 150.41 (b) 147.35	13.53 13.50	 33 32	28
 34	108.8	12.4	 35	36

the ease of the ring-opening and also leads solely to the (E)-product,[19] as shown in scheme 7.

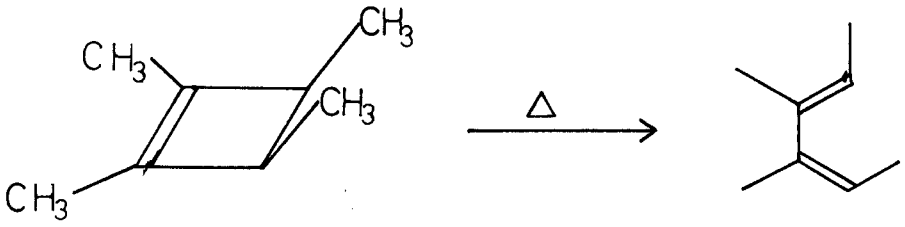
Scheme 7



(19) (20)

An estimate of this repulsion can be obtained from a comparison of trans (23) and cis (25) -1,2,3,4-tetramethylcyclobutenes, where the 16 k.joules $mol.^{-1}$ difference between the two activation energies can be attributed mainly to the twisting of a methyl group into the plane of the ring (scheme 8).

Scheme 8

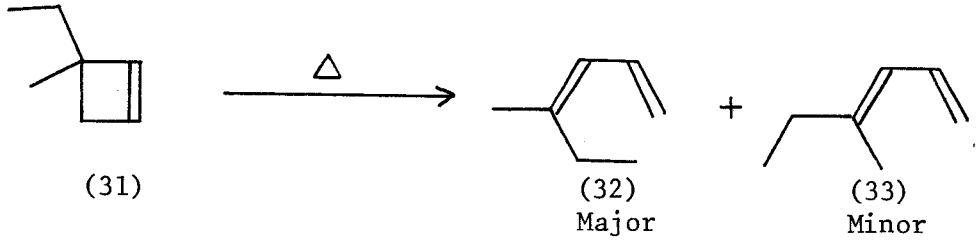


(25) (26)

Similarly, di-substitution at the 3-position leads to an increase in the activation energy, since one of the substituents has to rotate

into the ring. However, the ring-opening of 3,3-diethylcyclobutene (29) was found to be easier than that of 3,3-dimethylcyclobutene (27), indicating a preference for twisting an ethyl group into the plane of the ring. This is confirmed by a study of 3-ethyl-3-methylcyclobutene (31) where the (Z)-diene (32) is the major product (scheme 9), with an activation energy difference between the formation of the (Z) and (E) products of 3.0 k.joules $mol.^{-1}$.

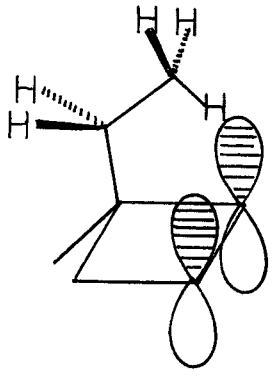
Scheme 9



(31) (32) Major (33) Minor

At 180° the (Z)-diene (32) is formed to the extent of 68% of the product, though examination of models does not show any less interaction when the ethyl group is twisted into the plane of the ring compared to the methyl group. This result was explained by an interaction between the π electrons of the double bond and the electrons of the terminal carbon-hydrogen bonds of the ethyl group[28] as illustrated in figure 3.

Figure 3

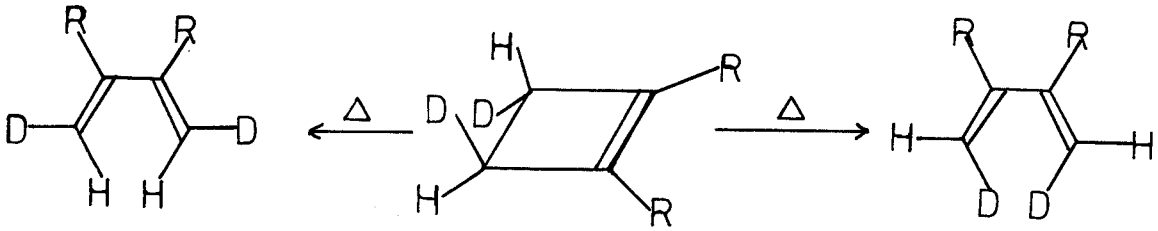


Rotation of the ethyl group can bring these terminal hydrogens into close proximity to the double bond, and as the ethyl group is then partly over the plane of the ring it will require less energy to twist into the plane compared to the methyl group. Such an interaction is not possible with the methyl group.

A study of further 3,3-disubstituted cyclobutenes should be able to check this explanation, and this has been the concern of the work presented in this thesis.

Winters and Honig[38] have carried out other work on the ring-opening of cyclobutenes via the competitive, conrotatory paths. The synthesis of the deuterated cyclobutene (36) was accomplished by an acyloin reaction using trimethylchlorosilane. At 180° the half-life of the isomerisation was approximately 90 minutes and yielded the (E,E)-diene (38) as the major product (scheme 10).

Scheme 10



(37)
47.7%

(36)

(38)
52.3%

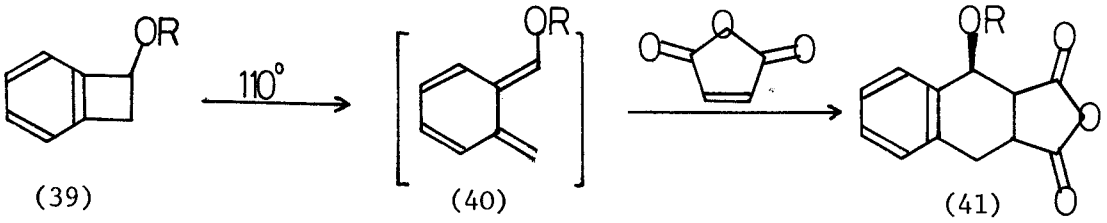
R = $OSiMe_3$

This was accounted for by a 'steric' deuterium isotope effect, whereby the smaller carbon-bound deuterium atoms should experience less

interaction when twisting into the plane of the ring compared to the hydrogens.

Studies on benzocyclobutenols by Sammes[39-41] and his coworkers have yielded results which show the effects of electronic factors on the ring-opening of these compounds. Thus the thermal isomerisation of the benzocyclobutenols (39), in the presence of maleic anhydride, gave the adducts (41) derived from the (E)-dienols (40),[39,40] as shown in scheme 11.

Scheme 11



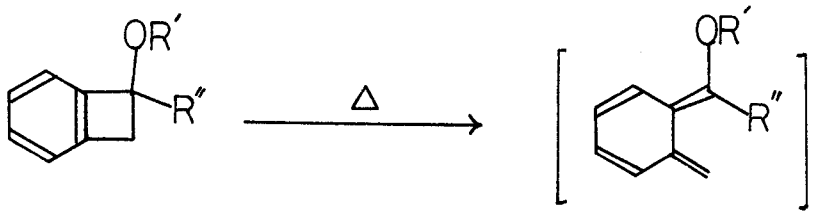
(39) (40) (41)

R = H, Me, OAc.

The rates of trapping varied OMe > OH >> OAc , showing a powerful inductive effect occurring on the ring-opening (since the cycloaddition reaction is very rapid and is not the rate determining step).

Disubstituted benzocyclobutenols (42) have available the two conrotatory modes of opening, though only products of the (E)-dienols (43) are observed[41] (scheme 12).

Scheme 12



Solely

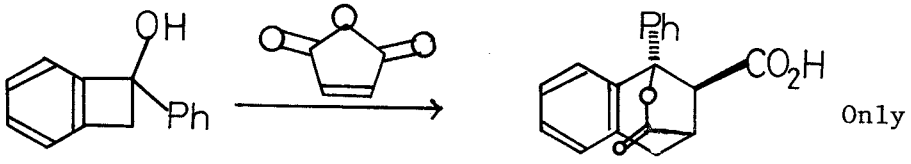
(42) (43)

$R' = H$; $R'' = Ph, CH{=}CH_2, Me$.

$R' = Me$; $R'' = Ph, Me$.

These dienols have been detected by either trapping experiments (scheme 13) or by further rearrangements (scheme 14), the ring closure in the transient species (47) occurring via a thermally-allowed disrotatory process.

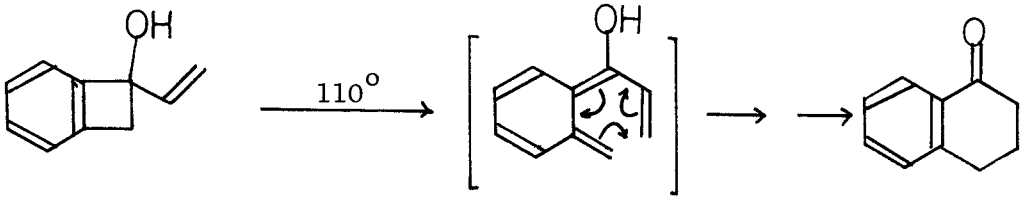
Scheme 13



Only

(44) (45)

Scheme 14

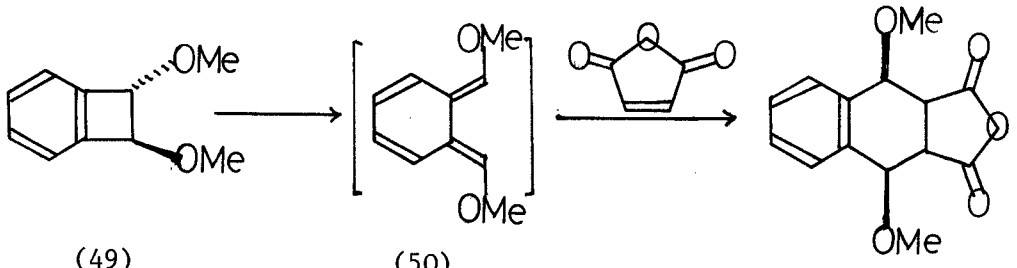


(46) (47) (48)

α-tetralone

It was noted that both the vinyl and phenyl substituents increased the rate of the electrocyclic reaction. These results show that the oxygen moiety does not rotate into the plane of the ring during the isomerisation, despite the larger size of the methyl and phenyl substituents. This has been comfirmed by the preparation and pyrolyses of cis (52) and trans (49) -1,2-dimethoxybenzocyclobutene. The trans isomer (49) was unstable at room temperature and gave the expected adduct with maleic anhydride as shown in scheme 15.

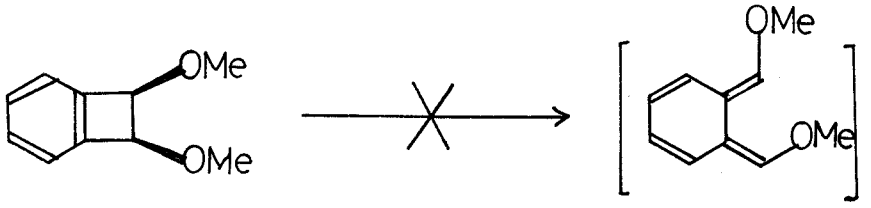
Scheme 15



(49) (50) (51)

The cis isomer (52) however was a very stable compound, giving no reaction at all with maleic anhydride and undergoing only general decomposition when heated to temperatures greater than 140° (scheme 16).

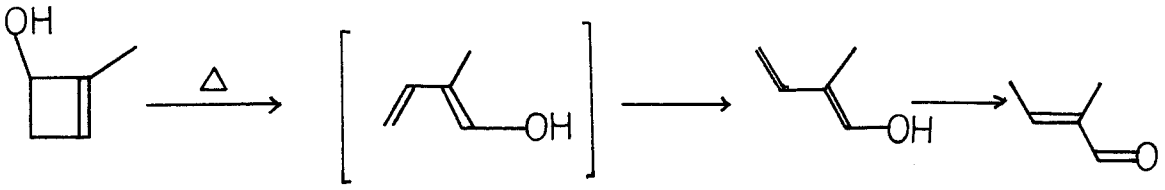
Scheme 16



(52) (53)

Jefford and his coworkers[42] have found similar results during their work on the parent cyclobutenols. Thus 2-methylcyclobut-2-enol (54) afforded only tiglic aldehyde (57) in quantitative yield, arising from the (E)-dienol (55) as illustrated in scheme 17.

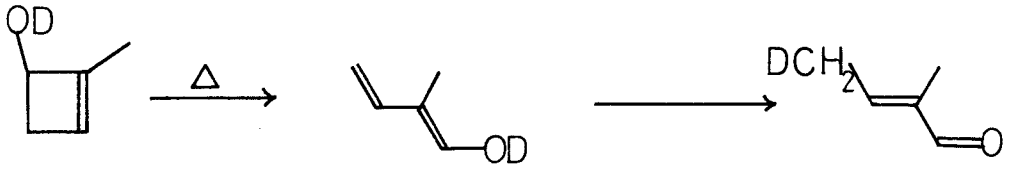
Scheme 17



(54) (55) (56) (57)

Confirmation of this was achieved by the pyrolytic behaviour of the deuterated analogue (58), which gave only the single product (59) and which, on further heating, yielded the monodeuterated tiglic aldehyde (60) shown in scheme 18.

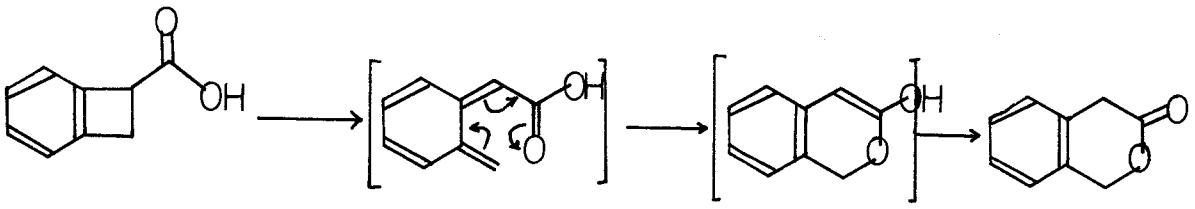
Scheme 18



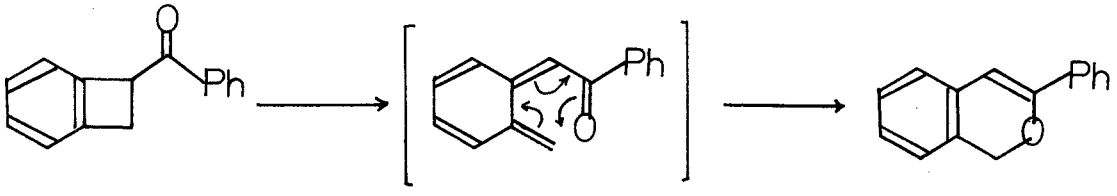
(58) (59) (60)

Hug[44] has also noted the ring-opening of acyl-benzocyclobutenes, which appears to give products derived from the (Z)-diene only (scheme 19).

Scheme 19



(61) (62) (63) (64)

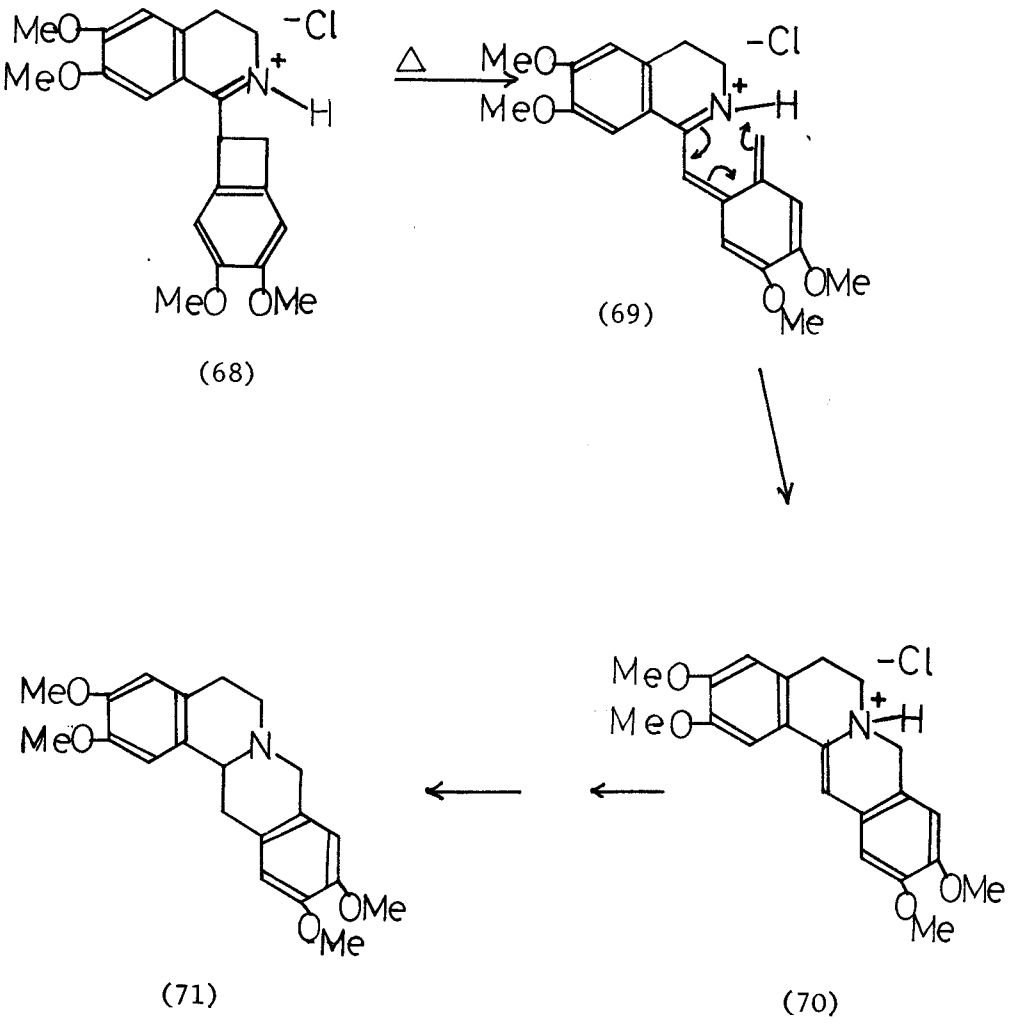


(65) (66) (67)

Distinction can now be made between those compounds having an occupied orbital adjacent to the ring (the benzocyclobutenols), which give rise to (E)-dienol products, and those having a vacant orbital adjacent to the ring (the acyl derivatives), which give (Z)-diene products.

The preparation of the natural product (±) Xylopinine (71), by thermolysis from 1-benzocyclobutenylisoquinoline,[43] provides a further demonstration of the electronic control of the ring-openings of benzocyclobutenes, shown in scheme 20. Heating the salt (68) rapidly yielded the ammonium salt (70), formed via the (Z)-diene species (69). However, on heating, the free base of compound (68) gave an unidentified product, presumably because the (E)-diene is then favoured.

Scheme 20

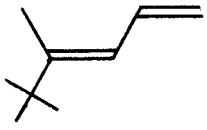


These results show that the electronic effects of substituents, such as the presence or absence of unshared electrons, must play an important role in the determination of the course of the electrocyclic reaction.

Nomenclature

The majority of the 1,3-dienes referred to in this section are of the substituted pentadiene type as shown below:

Correct nomenclature, however, often includes the R substituent in the longest chain, the compound then being classed as a hexadiene, heptadiene, etc. To facilitate the following of the arguments, the dienes are referred to by the R group present.

e.g.  t-butyldiene (134) etc.

The designation of the stereochemical prefixes Z and E is according to IUPAC rules,[108] where the stereochemistry about a double bond is determined by a sequence rule, closely following the size of the substituents. Thus in all cases Z or E are determined by the position of the R group with respect to the vinyl group as shown below:

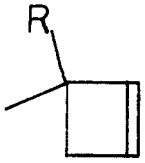
CHAPTER 2

RESULTS AND DISCUSSION

Synthesis of the cyclobutenes

For this study of the thermal isomerisation of cyclobutenes, by alternate stereochemical pathways, the following cyclobutenes were synthesised (Figure 4).

Figure 4



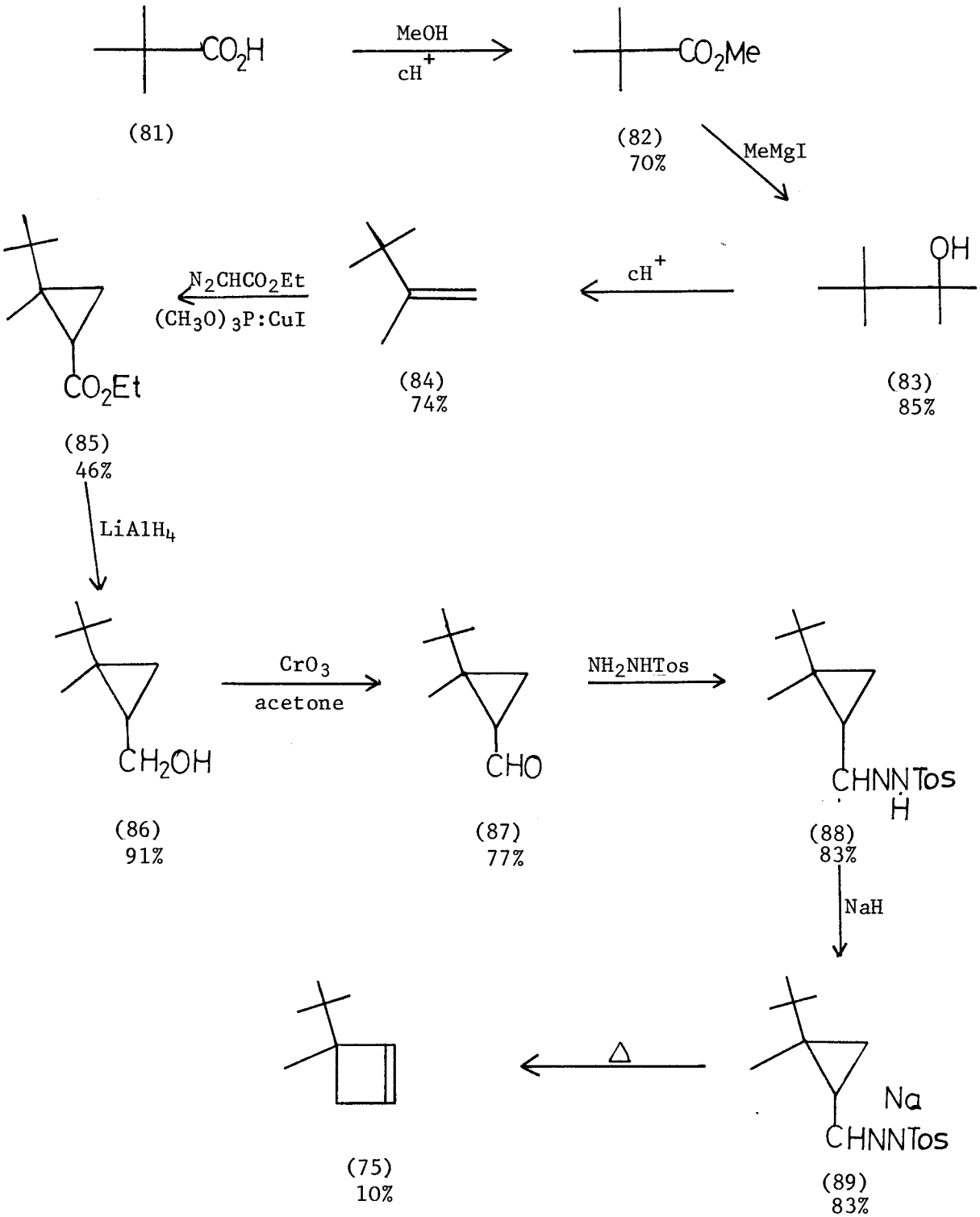
(72 - 80)

R = i-propyl (72), n-propyl (73), cyclopropyl (74), t-butyl (75), pentadeuteroethyl (76), phenyl (77), p-methoxyphenyl (78), m-methoxyphenyl (79), p-cyanophenyl (80)

Initially, the t-butyl compound (75) was prepared by a modification of the method used by Frey and his coworkers[25,27,28] for similar compounds, where the major step involved the rearrangement of a specifically substituted cyclopropyl carbene into the cyclobutene. The reaction sequence for the preparation of this compound is shown in scheme 21.

The reaction of ethyl diazoacetate with the alkene (84) was catalysed by a soluble copper(I) species, trimethyl phosphite: copper(I) iodide, first prepared by Arbusov[45,46] and later described by Moser.[47] The effect of this catalyst on the decomposition of the diazo compound has been studied by Peace and Wulfman,[48-51] who have found that the yields of

Scheme 21

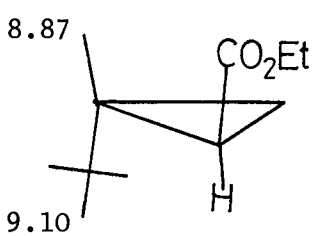


(% figures are isolated yields for each step)

addition products in these reactions are nearly double those using heterogeneous catalysts. These yields are strongly dependent on the catalyst concentration,[49] and the purity of the alkenes used. Thus Moser,[47] using highly purified and peroxide-free alkenes, had to employ almost 40 times the catalyst concentration that Peace and Wulfman found gave maximum yields when using alkenes that contained a few milligrams of benzoyl peroxide.[50] However, it was demonstrated[48] that the carbenoid process was not radical initiated but rather involved a change of catalyst, since treatment of the catalyst with benzoyl peroxide prior to the addition of alkene or diazo compound resulted in the formation of another catalyst far superior to any previously observed. The mechanism of the catalysis has been explained by a scheme involving attack of the diazo compound upon a catalyst-alkene complex with displacement of the associated anion, and loss of nitrogen from the resulting diazonium ion. This is followed by displacement of the carbene by the anion and then addition of the carbene to the alkene substrate.

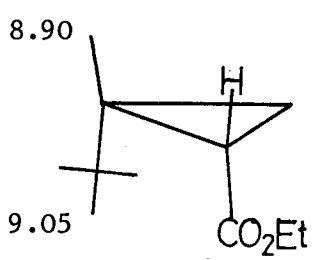
Steric effects present in the alkene (84) during addition of the carbene lead to the formation of the trans cyclopropyl ester (85a) as the major product, demonstrated by the downfield shift in the N.M.R. of substituents cis to the carbethoxy group (figure 5).

Figure 5



(85a)

trans 70%

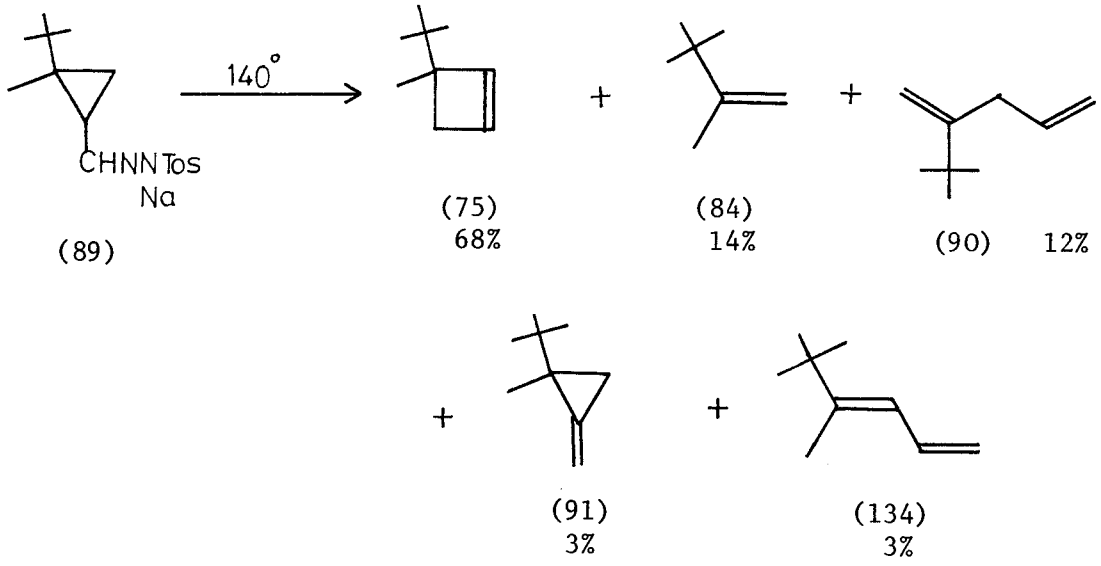


(85b)

cis 30%

Decomposition of the tosylhydrazone (88) was accomplished by vacuum pyrolysis of the sodium salt (89), at an optimum temperature of 140°. Above this temperature, and under the reaction conditions used, the products were shown to isomerise; below 140° reaction yields were markedly decreased. The complex mixture of volatile products, obtained from the decomposition, was separated into its major components by preparative g.l.c. and found to be as shown in scheme 22, the total yield being 48%.

Scheme 22

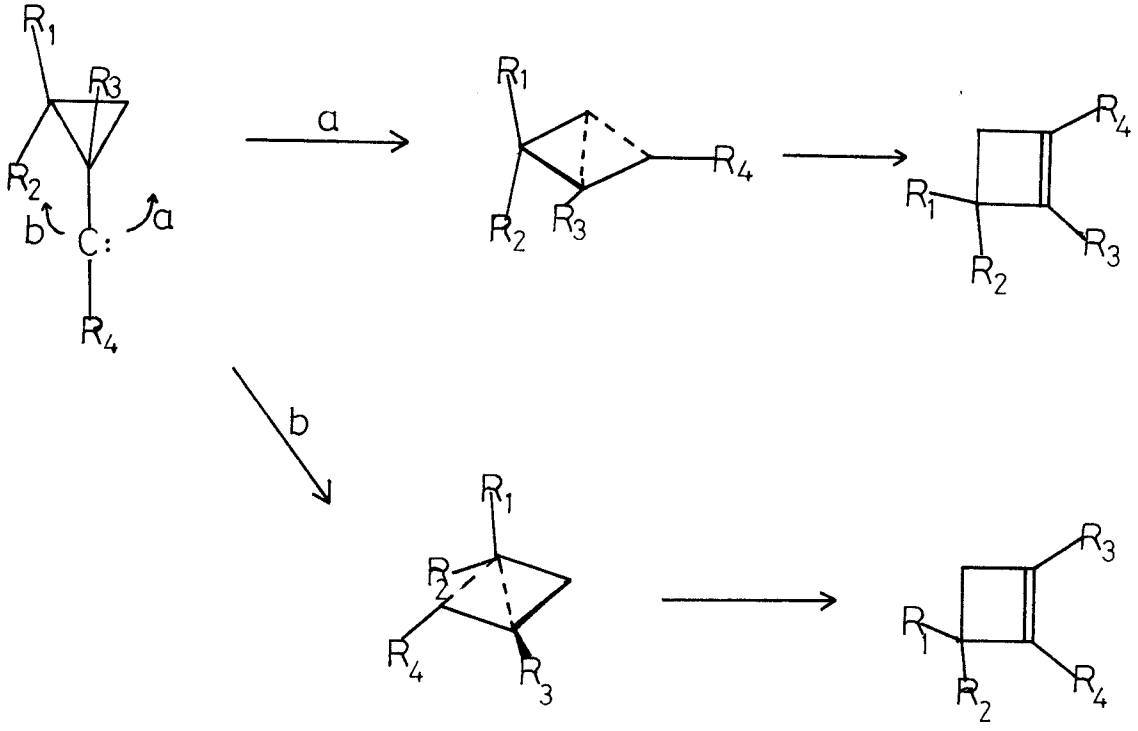


These products can be rationalised as arising from the intermediate cyclopropyl carbene, and its subsequent modes of decomposition. Thus, the alkene (84) is produced by a fragmentation reaction of the carbene, which would also yield acetylene though this would not have been trapped under the work-up procedure used. A 1,2-hydrogen migration yields the

methylene cyclopropane (91), though the predominant reaction path is the rearrangement to the desired cyclobutene (75).

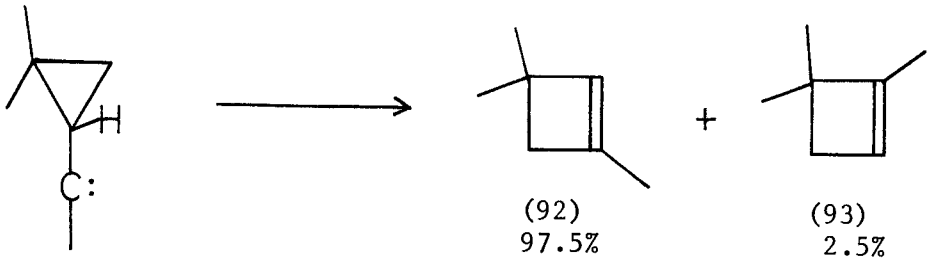
Stevens, Frey and Bird[52] have shown that the products obtained from the rearrangement of cyclopropyl carbenes are dependent on the steric effects present in the transition state. These effects are illustrated in the rearrangement of unsymmetrically substituted cyclopropanes as shown in scheme 23. Conversion to the cyclobutene involves rotation of the "carbene" carbon into the plane of the ring, either via route (a) or route (b) depending on whether the interaction between R_1, R_2 and the "carbene" carbon is larger or smaller (respectively) than that between R_1, R_2 and R_3.

Scheme 23



Thus, when $R_1 = R_2 = CH_3$, $R_3 = H$ and $R_4 = CH_3$, route (a) predominates since then $R_3 < R_4$, as shown in scheme 24.

Scheme 24



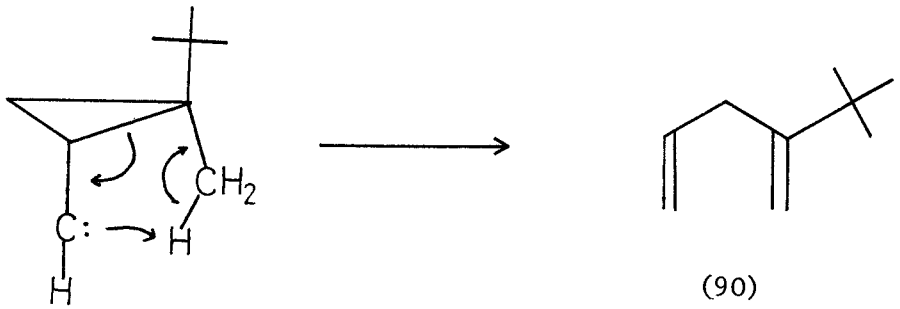
(92)
97.5%

(93)
2.5%

However, for the disubstituted cyclopropane in question, both routes lead to the same product, since $R_3 = R_4 = H$.

Of the other products isolated from the decomposition reaction, the (E)-1,3-diene (134) could have been formed directly from the carbene, though more likely it would arise from isomerisation of the cyclobutene (75). No evidence of the (Z)-isomer (133), an expected product from this isomerisation, was found, though this could be accounted for by polymerisation of the (Z)-isomer in the reaction vessel at the elevated temperature. The presence of the 1,4-diene (90) can be explained as having arisen directly from the cyclopropyl carbene, via a 5-membered transition state of the type shown in scheme 25.

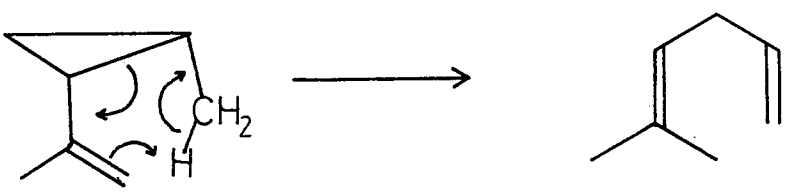
Scheme 25



(90)

Similar types of 6-membered transition states have been postulated for other cyclopropane rearrangements,[53] as for example the cis-methyl-vinyl cyclopropane (94), scheme 26.

Scheme 26

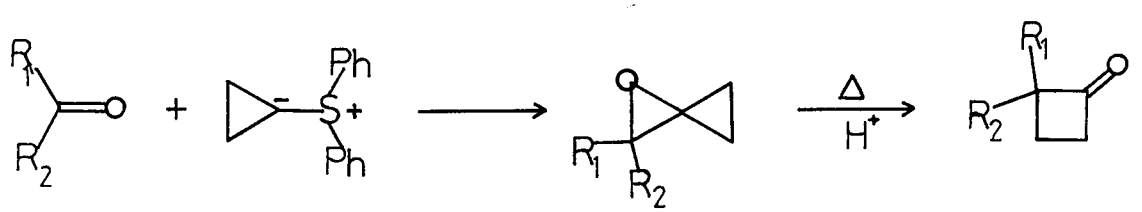


(94) (95)

The overall, isolated yield of the cyclobutene (75) amounted to no greater than 1%, and hence a more efficient and convenient method for the preparation of these compounds was required. Other known preparations, for example the acyloin condensation,[54,55] were also lengthy or of poor yield and so a new synthesis for these 3,3-disubstituted cyclobutenes was developed.

Work by Trost,[56-59] on the preparation of substituted cyclobutanones from ketones and sulphur ylids, has yielded excellent results as described in preliminary reports. A two-stage reaction produces cyclobutanones in almost quantitative yield, the reaction proceeding via the formation of the oxaspiropentanes, or spiroepoxides, as shown in scheme 27.

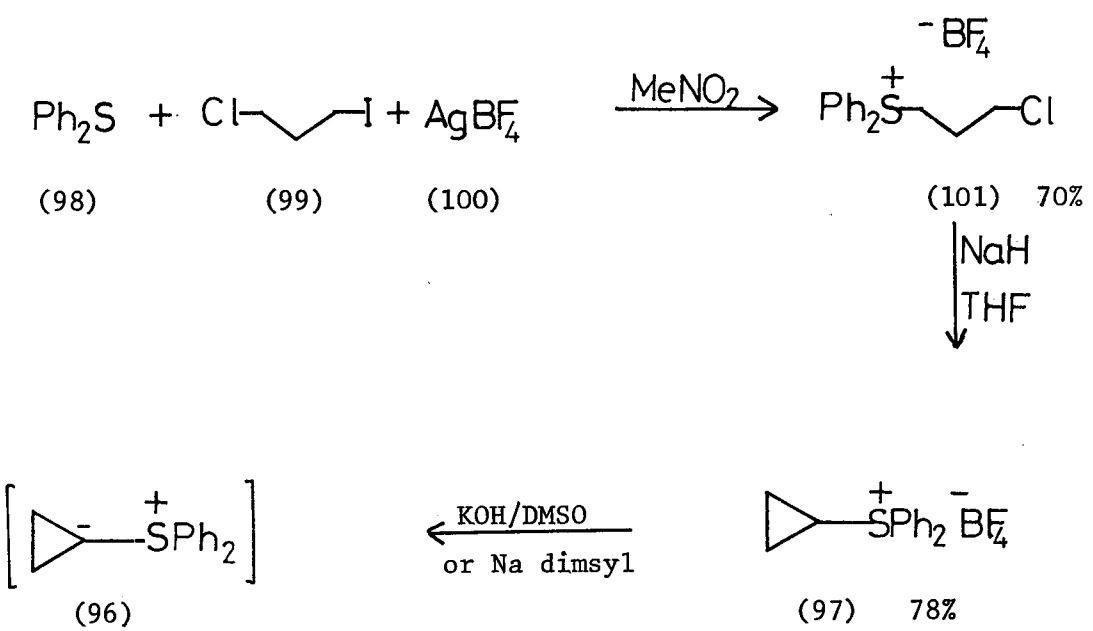
Scheme 27



(96)

Cyclopropyldiphenylsulphonium ylid (96) is among several sulphur compounds known to effect this reaction,[60-62] though since the precursor of compound (96) is an easily handled white, crystalline solid (97) this was the reagent of choice for the present work. Cyclopropyldiphenylsulphonium fluoroborate (97) was prepared as illustrated in scheme 28. However, though this reaction proceeded in good yield, large scale preparation was made impracticable by the high cost of starting materials.

Scheme 28

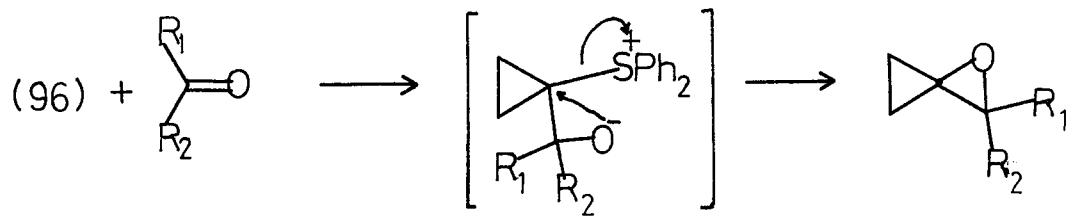


The preparation of the ylid (96) can be achieved in two ways, either irreversibly, using sodium methylsulphinyl carbanion at low temperature, or reversibly, using solid potassium hydroxide in dimethyl sulphoxide (DMSO) at room temperature. The latter method gave higher reaction yields,[57] and enabled the consequent reaction with the ketone to be

carried out "in situ" and so was used exclusively in this work.

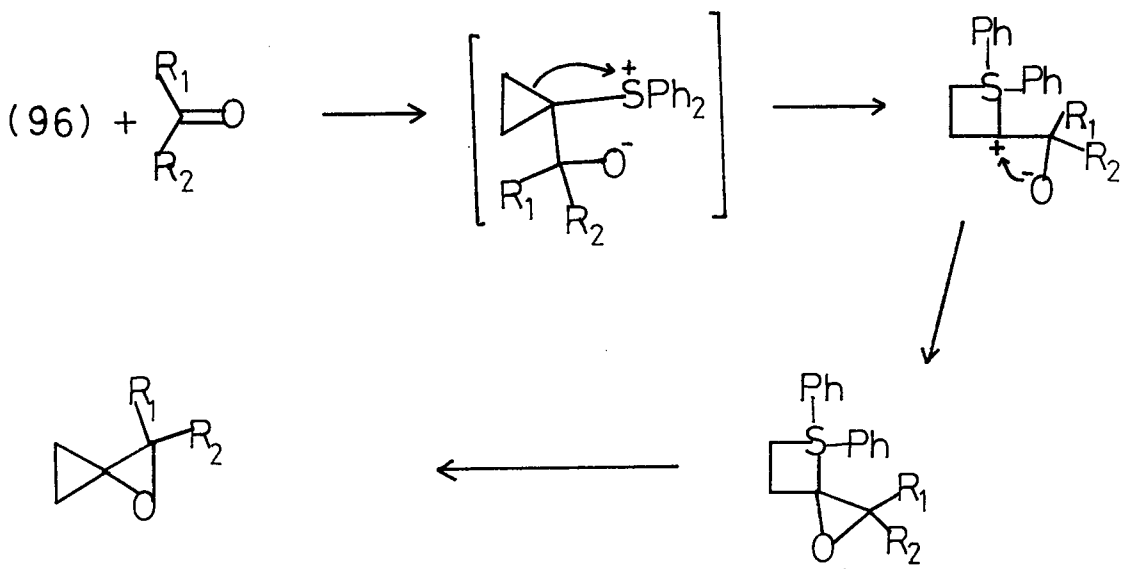
Reaction of the ylid (96) with a carbonyl species can be postulated to occur via two mechanisms.[58] Scheme 29 shows internal SN2 displacement, whereas scheme 30 involves sulphurane formation.

Scheme 29



(102)

Scheme 30



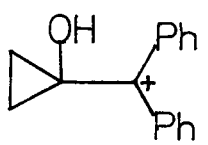
(103)

Elimination of diphenyl sulphide (Ph_2S) from the cyclopropyl ring in the intermediate betaine (102) is a facile process even at low temperature. However, treatment of the sulphonium salt (97) with sodium deuteroxide (NaOD) in D_2O at 75^{o} for 2 hours yields only complete

deuterium incorporation ∝ to sulphur and no decomposition. The SN2 displacement, even intramolecular, must then be suspect as illustrated in scheme 29. The sulphurane (103) formation, and subsequent collapse to the oxaspiropentane (scheme 30), is consistent with other observations and results, and indeed the collapse of a 4-membered sulphurane has been observed.[63] This would then seem to be the most probable mechanism of the reaction.

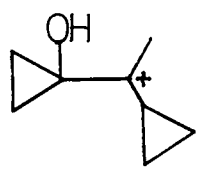
Conversion of the oxaspiropentanes to the corresponding cyclobutanones can be effected in a variety of ways.[57,64] The rearrangement can be induced thermally at temperatures around 100°, though treatment with Lewis acids or aqueous acids is more efficient. In particular, lithium perchlorate in benzene or aqueous fluoroboric acid are used where possible. In two instances[58] oxaspiropentanes are not formed in the reaction, these being with cyclopropylmethyl ketone and diphenyl ketone. The cyclobutanones are produced directly, presumably because of the stability of the carbonium ions (figure 6) and their rapid rearrangement.

Figure 6



(104)

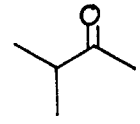
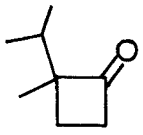
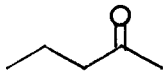
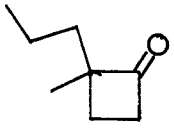
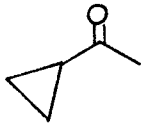
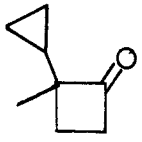
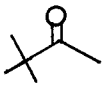
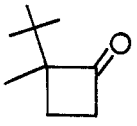
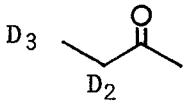
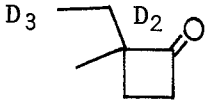
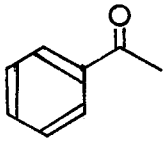
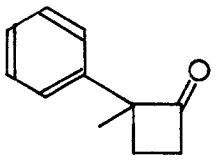
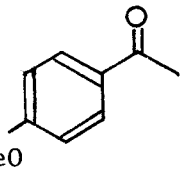
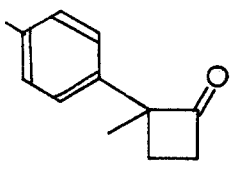
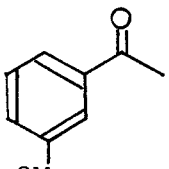
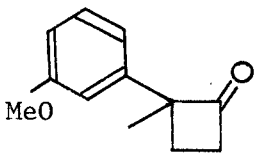
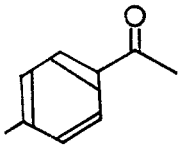
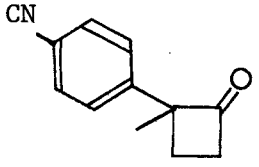
and



(105)

Development of this synthetic method was achieved in the present work, whereby cyclobutanones were produced directly by work-up of the crude reaction mixture with aqueous fluoroboric acid and extraction, to give isolated yields of pure materials in some cases approaching 100%.

Table 2: Preparation of Cyclobutanones

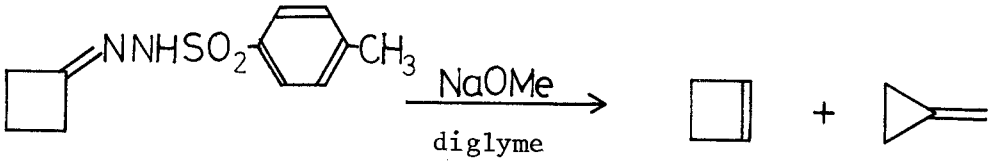
Ketone	Reaction Time (hours)	Product	Yield
 106	22	 107	44%
 108	12	 109	83%
 110	15	 111	60%
 112	24	 113	57%
 114	3	 115	65%
 116	4	 117	85%
 118	5	 119	93%
 120	4	 121	96%
 122	3	 123	87%

This technique was later confirmed by the publication of complete experimental details by Trost.[65]

The cyclobutanones prepared by this method are shown in Table 2.

With cyclobutanones now readily available, routes for the conversion to cyclobutenes were investigated. Friedman and Schechter[66] observed that decomposition of the p-toluenesulphonylhydrazone (tosylhydrazone) derivative (124) of cyclobutanone, with sodium methoxide, gave cyclobutene (13) as a minor product, with methylene-cyclopropane (125) as the major component (scheme 31).

Scheme 31



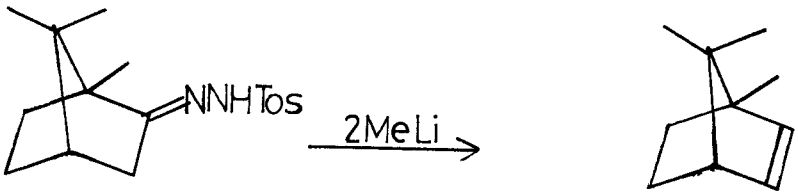
(124)

(13) 20%

(125) 80%

Later work by Shapiro[67-70] on tosylhydrazone decompositions,[71] using methyl lithium solutions, showed that alkenes could be produced from compounds having α hydrogens, even under unfavourable conditions[67,72] as illustrated in scheme 32.

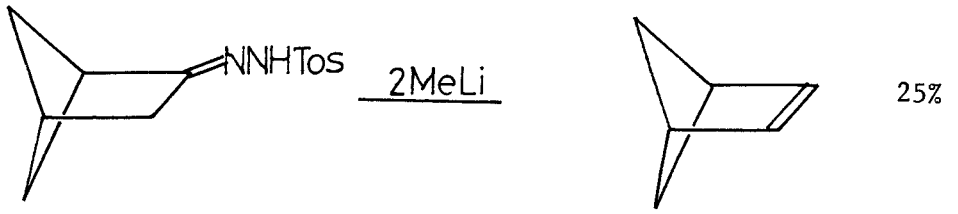
Scheme 32



100%

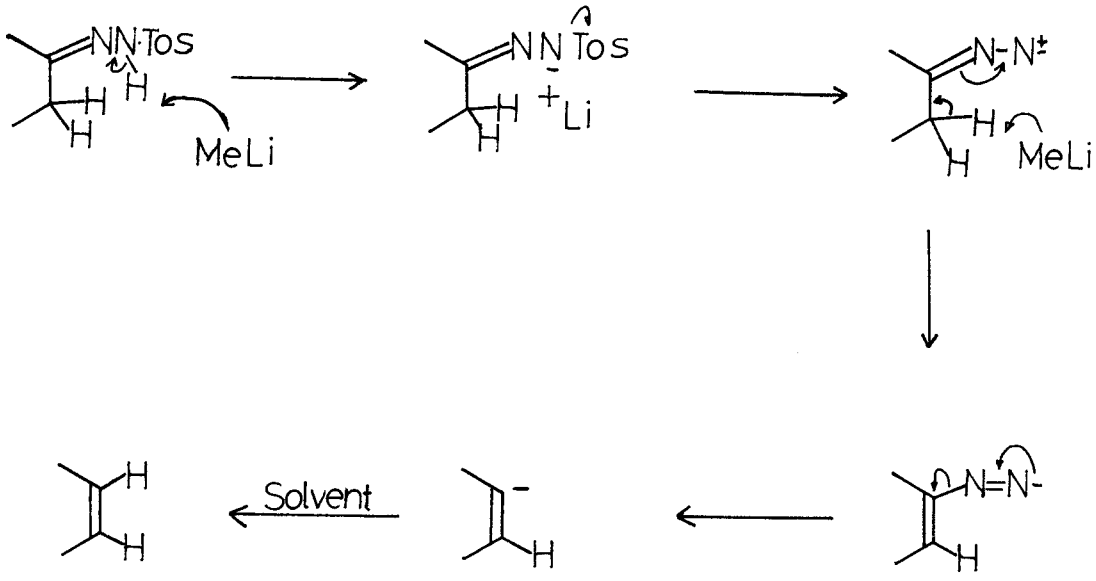
continued ..

Scheme 32 (continued)



The mechanism of the methyl lithium decomposition is shown in scheme 33.

Scheme 33

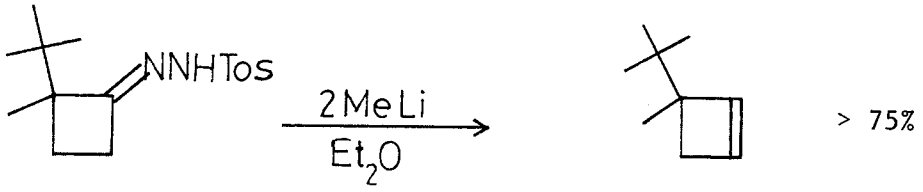


The formation of the lithium salt by the first mole of base is followed by loss of the tosyl anion, and removal of an α proton by the second mole of base. Loss of nitrogen and proton abstraction from the solvent gives the alkene. As a general rule, aliphatic tosylhydrazones

with α protons react with 2 moles of methyl lithium solution to give the unrearranged, less-substituted alkene. This method also favours cis olefin formation more than other methods, in particular carbenoid and carbonium ion decompositions.[68]

Initial application of this technique, on a small scale, to the tosylhydrazone of 2-t-butyl-2-methyl cyclobutanone (126) gave the cyclobutene (75) as expected (scheme 34), identified by g.l.c. comparison with the authentic sample previously synthesised. Development of this method for the cyclobutene preparation enabled isolated yields of greater than 75% to be obtained - purification being by solvent removal and vacuum-line distillation. All products were shown to be greater than 99% pure, by g.l.c.

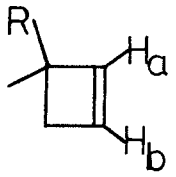
Scheme 34



(126) (75)

Since the methyl lithium decomposition affords the less-substituted alkene, it should be possible to apply this method to the synthesis of mono-substituted cyclobutenes, giving a convenient route to the more unusual members of the 3-substituted cyclobutene series.

The cyclobutenes prepared by this route are shown in figure 4, and were identified by NMR spectroscopy, this data being presented in Table 3.

Table 3: N.M.R. Data for 

. Chemical shifts are in p.p.m. (τ) and J values in Hz.

R	CH_3	CH_2 (ring)	H_a	H_b	Others		No.
i-propyl	8.94	7.98 & 7.78	3.92	4.03	CH_3 i-propyl 9.15	C-H i-propyl 8.34	72
	(s)	sd(13.0) bd(13.0)	(sd,2.5)	(bd,2.5)	(t,7.5)	(septet,7.5)	
n-propyl	8.88	7.90 & 7.78	3.94	4.04	CH_3 n-propyl 9.11	$(CH_2)_2$ 8.5 - 8.80	73
	(s)	sd(12.0) bd(12.0)	(sd,2.0)	(bd,2.0)	(t,7.5)	(c)	
cyclopropyl	8.85	7.92	4.26	4.05	CH_2 ring 9.6 - 10.10	-CH ring 9.2 - 9.50	74
	(s)	(bs)	(sd,3.0)	(bd,3.0)	(c)	(c)	
t-butyl	8.80	8.11 & 7.51	4.01	4.05	CH_3 t-butyl 9.10		75
	(s)	sd(13.2) bd(13.2)	(sd,2.6)	(bd,2.6)	(s)		
pentadeutero ethyl	8.87 (s)	7.89 & 7.77 sd(13.0) sd(13.0)	3.95 (sd,2.8)	4.03 (bd,2.8)	-		76

continued ....

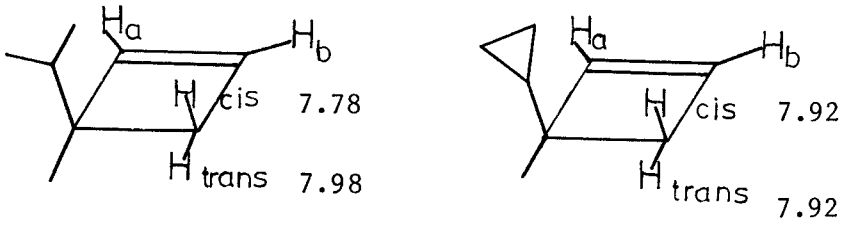
Table 3 (continued)

R	CH_3	CH_2 (ring)	H_a	H_b	Others		No.
ethyl	8.87	7.89 & 7.77	3.95	4.03	CH_3 ethyl	CH_2 ethyl	
					9.13	8.52	31
	(s)	sd(13.0) sd(13.0)	(sd,2.8)	(bd,2.8)	(t,7.5)	(q,7.5)	
phenyl	8.45	7.35	3.56	3.82	aromatic		
					2.77		77
	(s)	(bs)	(sd,2.5)	(bd,2.5)	(c)		
p-methoxy	8.50	7.41	3.62	3.85	CH_3 aromatic	aromatic	
					6.30	3.00	78
phenyl	(s)	(bs)	(sd,2.8)	(bd,2.8)	(s)	(ABq,8.5)	
m-methoxy	8.46	7.35	3.56	3.80	CH_3 aromatic	aromatic	
					6.21	2.6 - 3.40	79
phenyl	(s)	(bs)	(sd,2.5)	(bd,2.5)	(s)	(c)	
p-cyanophenyl	8.44	7.34	3.51	3.72	aromatic		
					2.40		80
	(s)	(bs)	(sd,2.5)	(bd,2.5)	(ABq,8.5)		

The protons, H_a and H_b, were assigned by a comparison of the iso-propyl (72) and cyclopropyl (74) spectra. Thus proton H_b resonates at the same frequency in both compounds, and in all the aliphatic compounds, whereas proton H_a is shielded in the cyclopropyl compound (74). This is consistent with the well known shielding effect of the cyclopropyl group.[73] It is assumed that this effect is greater the nearer the proton and so H_a must be the olefinic proton adjacent to the position of substitution. H_b exhibits a rather broader and shorter doublet than that of H_a, showing the extra coupling between H_b and the adjacent methylene group of the ring.

However, the two protons of the ring methylene group are magnetically different, appearing as an AB quartet with one half of the quartet being much broader and shorter than the other half. This corresponds to the broadening of H_b - showing the coupling of only one of the methylene protons to H_b. Which of the two protons is coupling can be identified by again comparing the iso-propyl and cyclopropyl spectra, the relevant resonances being shown in figure 7.

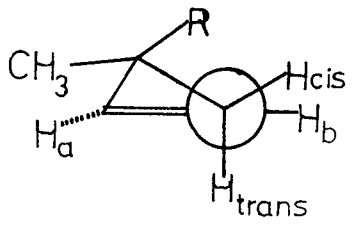
Figure 7



The methylene proton cis to the cyclopropyl group is significantly shielded compared to the same proton in the iso-propyl compound, whereas the trans proton remains approximately constant. This shielded proton

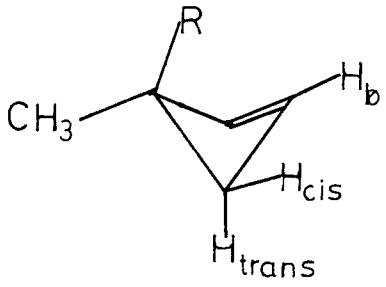
is the one showing the broadening from the coupling with H_b, and hence must be in a more planar configuration with H_b than the other, unbroadened, proton. This is illustrated in figure 8.

Figure 8



In this conformation H_{TRANS} is almost perpendicular to H_b and so shows no coupling. Also, it can be seen that the alkyl group, R, is in a "pseudo-axial" environment, better shown in figure 9.

Figure 9



This is rather unexpected on steric grounds, since the larger alkyl group, R, should tend to destabilise this axial conformation, as in the substituted cyclohexane series. However, examination of molecular models

shows that, when in this axial position, the alkyl group is partially over the plane of the ring - a pre-requisite for the interaction between the terminal protons of the alkyl group and the double bond as described in Chapter 1.

This effect of the twisted ring is shown markedly by the n-propyl (73), iso-propyl (72) and t-butyl (75) compounds, though in the cyclopropyl compound (74) the two methylene protons appear only as a broad singlet. As inferred previously, this singlet must be due to the accidental magnetic equivalence of the two protons and any differential coupling, between one of them and H_b, would be masked by the other resonance.

Surprisingly, the ethyl compound (31) does not show any twisting effect, the NMR spectrum showing both halves of the methylene AB quartet of identical height and peak width. Spin decoupling and INDOR experiments confirm that both of the methylene protons are coupled to H_b to an identical extent.

The NMR spectra of the aromatic-substituted compounds (77-80) all show the methylene group as a broad singlet, again most probably due to the coincidental overlap of the two signals rather than the equivalence of the protons. Attempts were made to separate this singlet into its two component resonances by a study of the NMR of the phenyl compound (77) at low temperatures. It was postulated that at low temperatures one particular conformation would be frozen out and display the unequal coupling of the methylene protons, though down to -54^{o} the whole spectrum remained constant. Conversely the NMR spectrum of the t-butyl compound (75) was investigated at high temperature, in an attempt to equilibrate the coupling constants of the methylene AB quartet by equilibration of

the axial/equatorial conformations. Again, no difference in the spectrum was observed, up to 130°. However, if this ring-twisting is expected to affect the product ratio of the isomerisation process by twisting the alkyl group into the ring, it should be expected to remain twisted through to the transition state of the process.

Pyrolysis of the cyclobutenes

Pyrolyses were performed in the gas-phase, in a glass vessel fitted with a Teflon valve, at a temperature of 180° in most cases and for a period in the order of 1 hour. Where the reaction was extremely rapid at 180° a lower temperature was employed, this applying in particular to the aromatic compounds. The data obtained from these reactions is presented in Table 4.

Assignment of pyrolysis product stereochemistry

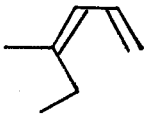
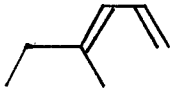
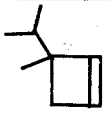
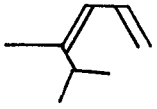
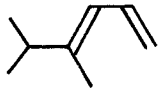
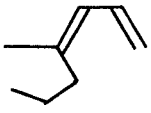
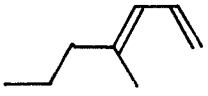
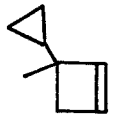
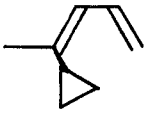
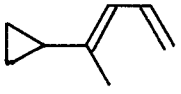
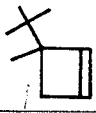
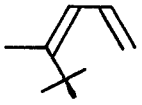
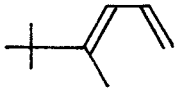
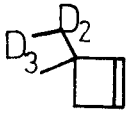
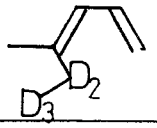
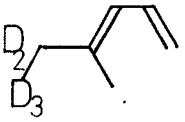
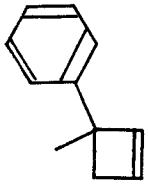
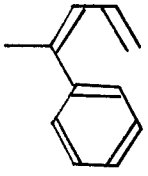
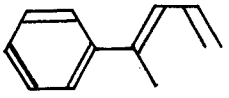
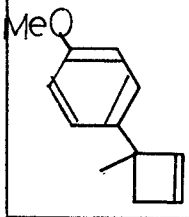
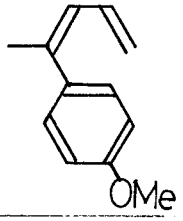
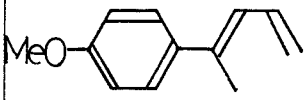
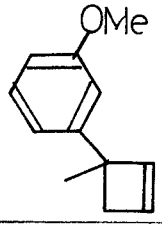
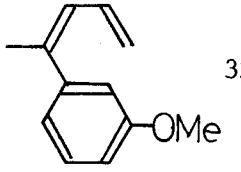
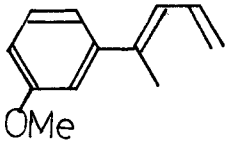
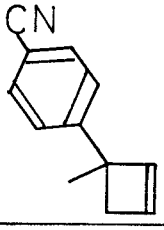
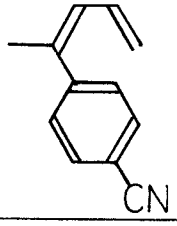
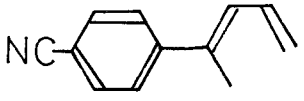
The Z and E-isomers obtained from the pyrolyses of the cyclobutenes were identified, in most instances, by g.l.c. comparison with authentic samples. These authentic samples were synthesised and identified as described below.

(a) Synthesis of the 1,3-dienes

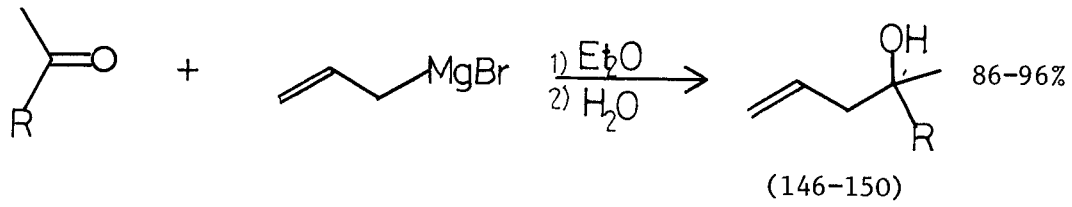
The 1,3-dienes were synthesised by the dehydration of the corresponding tertiary homoallylic alcohols.

The reaction of various ketones with allyl magnesium bromide in ether, followed by aqueous work-up, yielded the homoallylic alcohols in almost quantitative yields (Scheme 35).

Table 4: Pyrolysis of the cyclobutenes

Cyclobutene	% of product		Temp °C
	Z isomer	E isomer	
 (31)	 68% (32)	 32% (33)	180
 (72)	 65.5% (127)	 34.5% (128)	180
 (73)	 62% (129)	 38% (130)	180
 (74)	 43% (131)	 57% (132)	180
 (75)	 32% (133)	 68% (134)	180
 (76)	 61% (135)	 39% (136)	180
 (77)	 30% (137)	 70% (138)	180
 (78)	 52% (139)	 48% (140)	180
 (79)	 32% (141)	 68% (142)	161
 (80)	 45% (143)	 55% (144)	161

Scheme 35

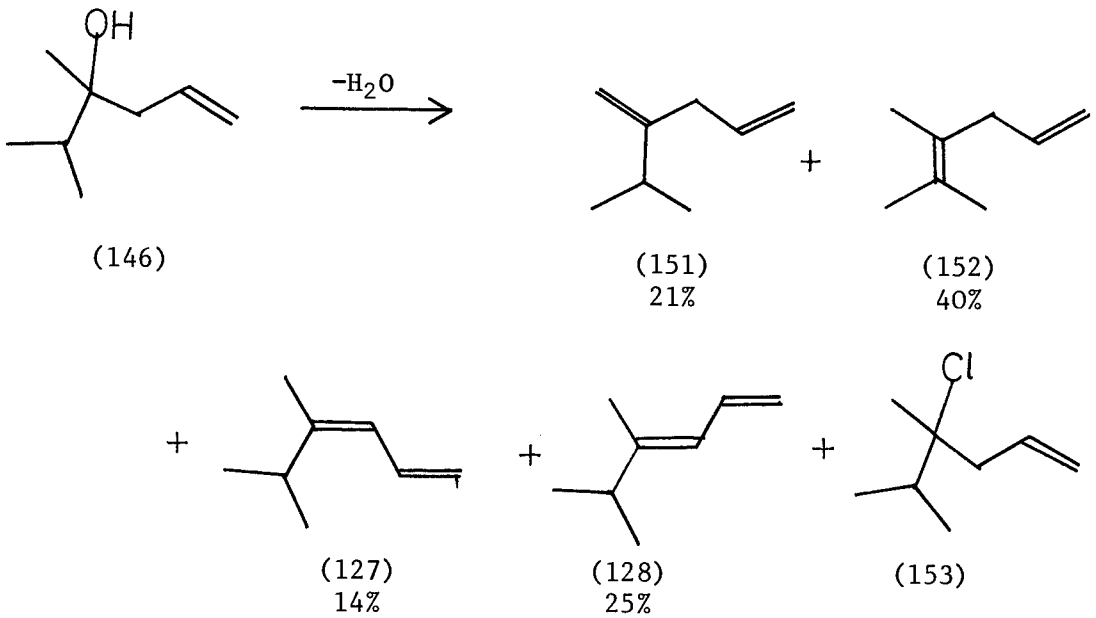


(146-150)

Dehydration of the alcohols was achieved using thionyl chloride ($SOCl_2$) in pyridine at 0^o, a modification of the method utilised by Lomas.[74] The products were obtained as complex mixtures of isomers, corresponding to the elimination of any available protons β to the hydroxyl group, and are illustrated in Schemes 36-39. The normal reaction conditions used by Lomas, involving stirring the reaction mixture at room temperature overnight, resulted in considerable polymer formation and very low yields. Consequently, stirring at 0^o for 3 hours, immediately followed by ethereal extraction, was found to improve yields up to the order of 50%.

Dehydration of homoallylic alcohols

Scheme 36



(146)

(151)
21%

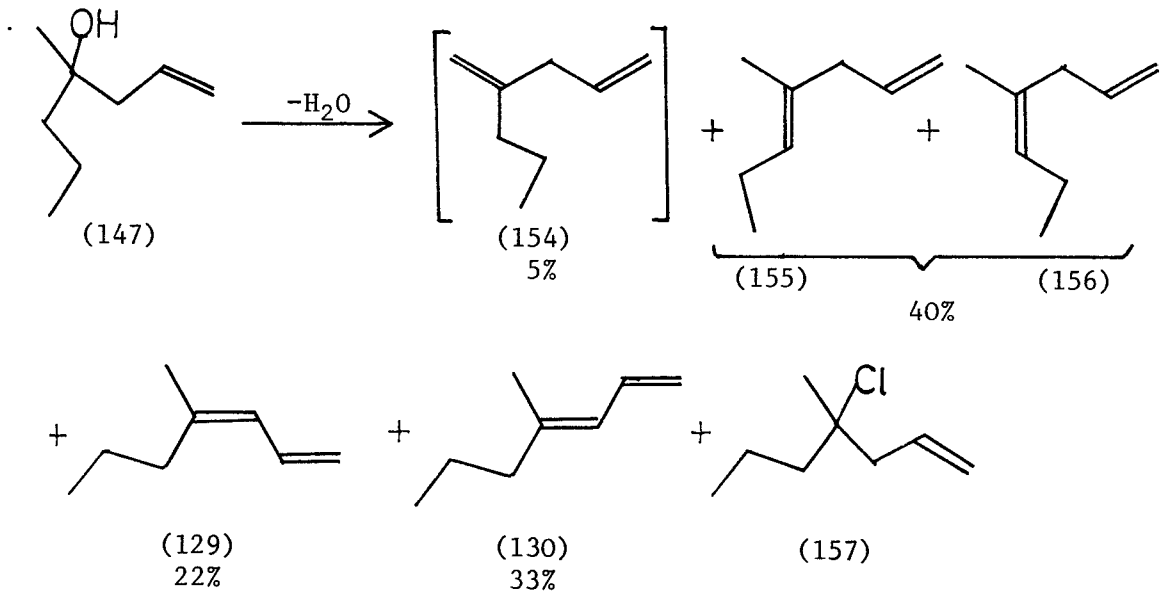
(152)
40%

(127)
14%

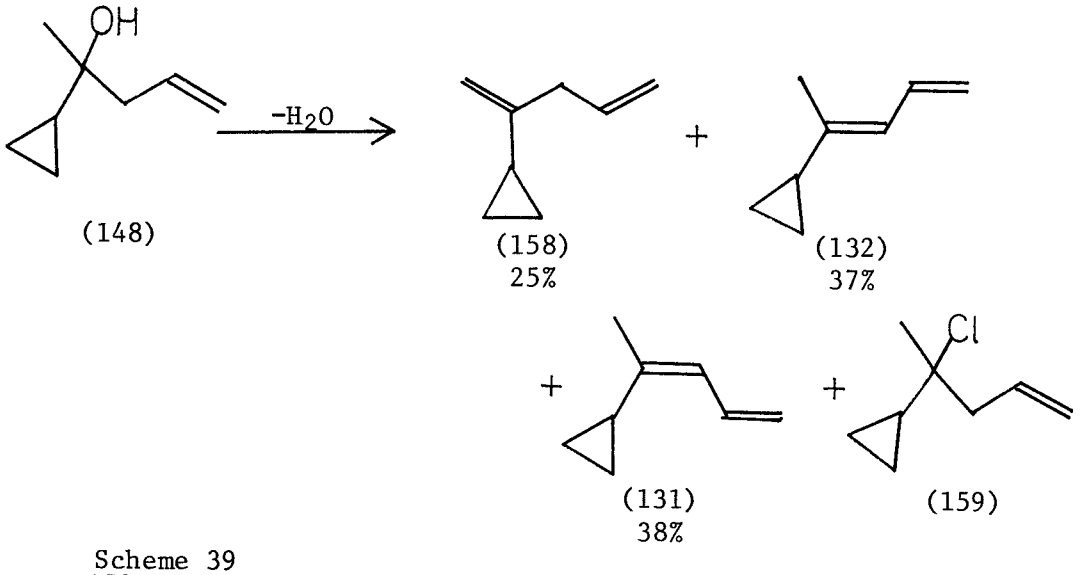
(128)
25%

(153)

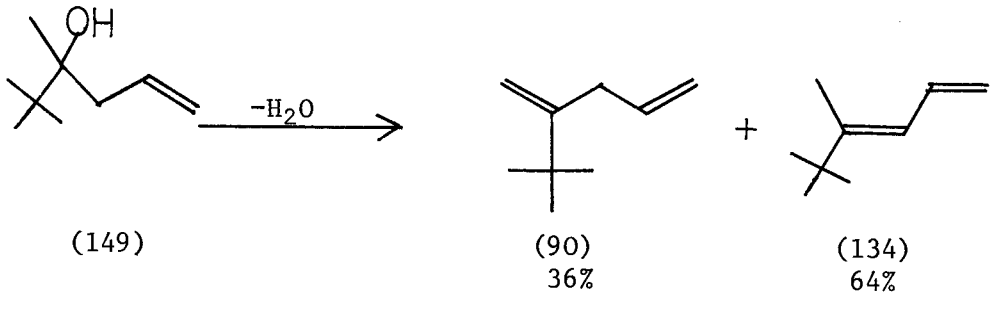
Scheme 37



Scheme 38

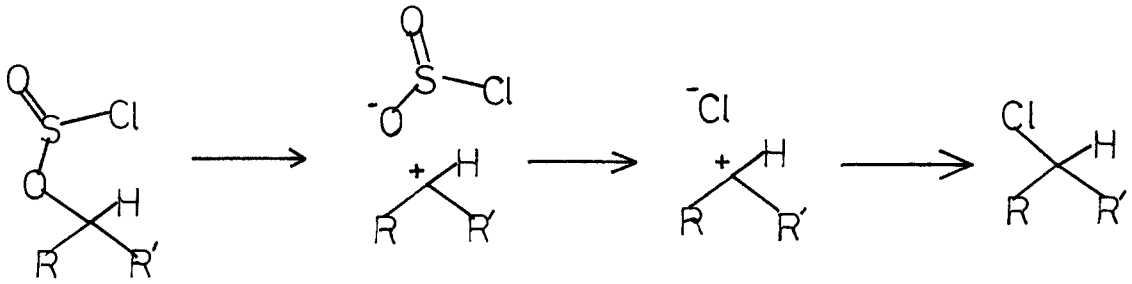


Scheme 39



The dehydration step involves the formation of the alkyl chlorosulphite and its subsequent elimination. Primary and secondary alcohols are well known for their reaction with thionyl chloride,[75] the chlorosulphites in these instances producing ion pairs, which subsequently yield the alkyl chlorides, as shown in Scheme 40.

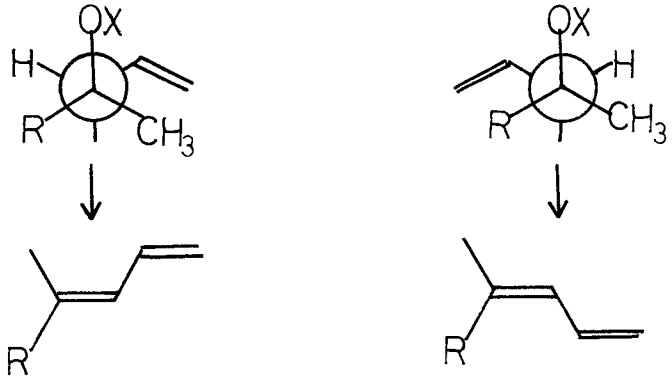
Scheme 40



The tertiary alcohols preferentially undergo elimination, though identification of minor quantities of the tertiary homoallylic chlorides in some reaction products indicates the intermediacy of the chlorosulphites.

A study of the ratios of Z/E-1,3-dienes produced by the elimination reaction, shows the favoured production of the thermodynamically more stable isomer - the E-diene. Newman diagrams of the intermediates involved show that the E-diene will be favoured when the substituent

Figure 10



R is larger than the methyl group (Figure 10), and the mode of elimination is antiperiplanar.

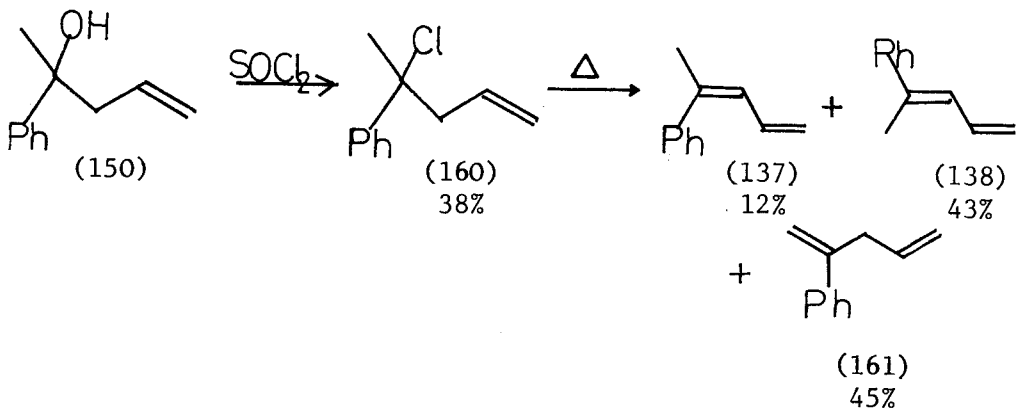
The steric interactions present are such that when R = t-butyl (149) none of the Z-diene is produced at all. The preparation of this Z-diene (133) was achieved by the photosensitised-irradiation of the E-isomer in the presence of acetophenone, using a medium-pressure mercury lamp. This gave a binary mixture of dienes containing 41% of the Z-diene.

Reaction of $SOCl_2$/pyridine with the phenyl-substituted homoallylic alcohol (150), instead of giving the expected hydrocarbon product, yielded solely the chloride (160) in about 38% yield. This low yield can be attributed to considerable polymerisation of any diene produced, leaving the chloride exclusively. Production of the chloride to the extent of 38% must be due to the enhanced stability of the tertiary carbonium ion formed, a consequence of the adjacent phenyl substituent.

However a small scale vacuum pyrolysis of the chloride (160) was performed at 190°, and subsequent g.l.c. analysis showed that 3 products were formed together with the starting material. This was attributed to the loss of HCl from the molecule, being confirmed by the mass spectrum showing a large peak at M-36. A large scale dehydrochlorination (and simultaneous separation of the products) was achieved by careful control of the injection port temperature of the preparative g.l.c. Injection of samples of the chloride into the port at 190° gave complete dehydrochlorination, and enabled the products to be collected after separation. These were identified as shown in Scheme 41. The 1,4-diene (161) and the (Z)-1,3-diene (137) were not fully resolved and were collected together, identification of the

Z-diene being postulated from a singlet in the N.M.R. of the mixture at 7.91 τ, corresponding to the methyl group.

Scheme 41



(b) Separation of the 1,3-dienes

Separation of the products of a dehydration reaction has afforded considerable difficulty since all hydrocarbon products are isomeric. Such techniques as fractional distillation, column chromatography and argentous t.l.c. have all proved inadequate, leaving g.l.c. as the only available method.

The separation of 1,4- and 1,3-dienes was achieved on a wide variety of column liquid phases, but separation of Z and E-isomers of the 1,3-dienes necessitated the very careful choice of both liquid phase and column conditions. In general almost complete resolution of the isomers, sufficient for accurate area measurement, could be obtained using analytical columns of polypropylene glycol adipate (PPGA) or 1,3-dicyanoethoxy propane (1,3DCEP). However, preparative columns could not achieve such resolution, thus requiring the use of small sample sizes,

'on-column' injections, long retention times and careful collection of each fraction to avoid excessive contamination. In certain cases fractions had to be re-chromatographed to obtain pure samples.

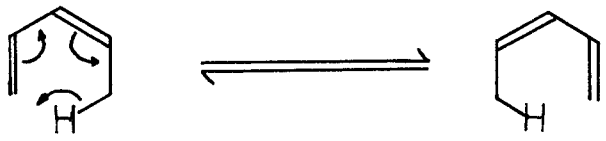
When collected in a pure state, especially when free from solvent, the 1,3-dienes were found to polymerise readily with the action of heat and light and hence required storage at low temperatures.

(c) Identification of Z and E-1,3-dienes

(i) 1,5-H shift

In substituted 1,3-diene systems that can adopt the required conformation, it is possible to use the 1,5-H shift[3] as a method of identification. This sigmatropic rearrangement involves the suprafacial transfer of a hydrogen atom[76] to the end of the diene system, via a 6-membered transition state as illustrated in Scheme 41, requiring the adoption of an s-cis configuration by the diene.

Scheme 41

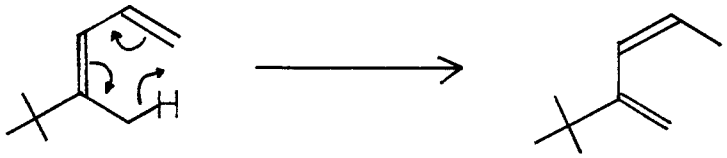


The 1,5-H shift in acylic dienes has been found to have an activation energy of around 134 k.joules mol^{-1} and to show large deuterium isotope effects.[77,78] For the purposes of identification the rearrangement was accomplished by vacuum pyrolysis of the compounds in a glass vessel, at

temperatures above 240°. After a suitable period the vessel was cooled and the products either washed out with pentane or distilled out on a vacuum-line. Analysis and separation of the products was by g.l.c., and identification by N.M.R.

Pyrolysis of the 1,3-diene isolated from the dehydration of the t-butyl homoallylic alcohol (149) yielded the further diene (162), identified by N.M.R., which must arise from the E-diene (134), as shown in Scheme 42.

Scheme 42

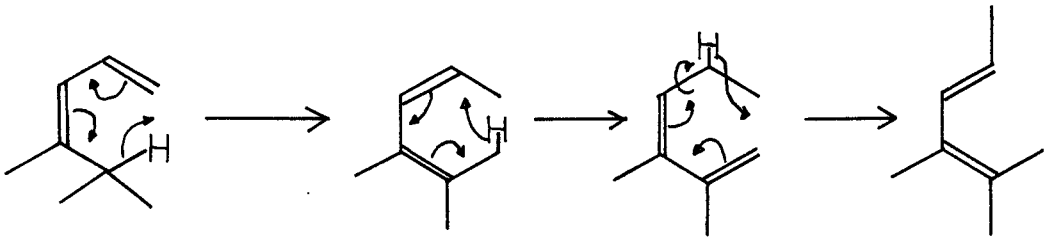


(134) (162)

Separation of the 1,3-dienes obtained from the dehydration of the i-propyl homoallylic alcohol (146) yielded one diene of shorter retention time (minor) on g.l.c. and one of longer retention time (major).

A small scale pyrolysis of the diene of shorter retention time gave a single product peak, though a large scale pyrolysis (70 mg) yielded 3 products. These were identified as shown in Scheme 43, and must have arisen from the Z-diene (127).

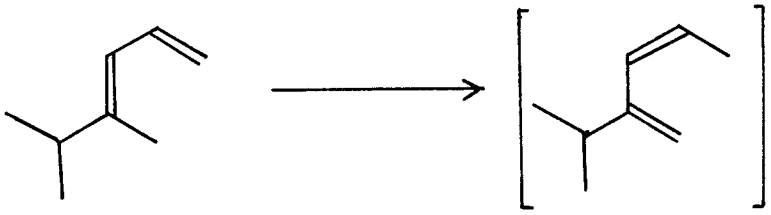
Scheme 43



(127) (163) (164) (165)

Pyrolysis at 250° for 2.0 hours converted 72% of the Z-diene (127) to products. However, the diene of longer retention time, the E-diene (128), on pyrolysis at 295° for 2.5 hours, gave only 18% reaction to a single unidentified product, presumably (166) as shown in Scheme 44.

Scheme 44



(128) (166)

This shows a considerable difference in reaction rate between tertiary and primary hydrogens during the 1,5 H shift, a fact as yet unaccounted for.

This method, however, could not be applied to the identification of the cyclopropyl dienes, due to the thermal vinylcyclopropane (167) - cyclopentene (168) rearrangement[79-82] (Scheme 45).

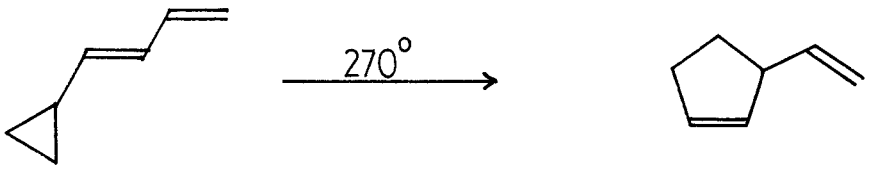
Scheme 45

(167) (168)

Although not occurring in vinylcyclopropane itself until around 340°,

the rearrangement has been found to be facilitated by the presence of a further vinyl group, as for example in (E)-cyclopropylbutadiene (169),[83] and to then occur at temperatures down to 270° (Scheme 46).

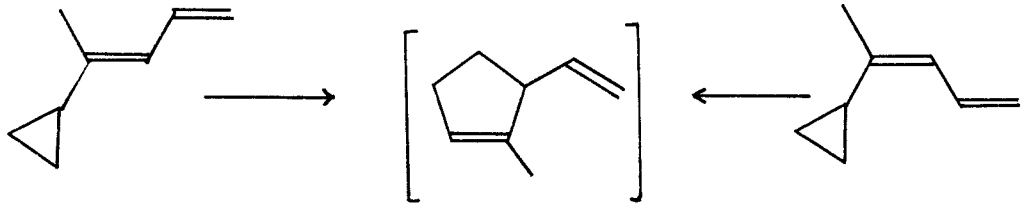
Scheme 46



(169) (170)

This rearrangement would interfere with any 1,5 H shift occurring at that temperature, particularly since both the cyclopropyl dienes in question would yield the same product (171) as shown in Scheme 47.

Scheme 47



(132) (171) (131)

Identification of these isomers has been achieved using ^{13}C N.M.R. as described below.

(ii) ^{13}C N.M.R.

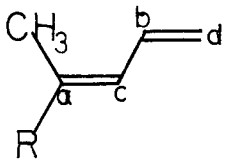
Broad-band proton-decoupled ^{13}C Fourier transform N.M.R. spectra, of the 6 dienes shown in Table 5, were recorded in $CDCl_3$ at natural abundance using approximately 100 mg of compound. Chemical shifts are quoted in p.p.m. downfield from Me_4Si. Off-resonance decoupling of the spectra allowed the resonances to be assigned as shown.

A study of the data for the Z and E-isomers of the i-propyl and t-butyl dienes enables several conclusions to be drawn concerning the chemical shifts of some of the carbon atoms. Those atoms showing the greatest and most consistent dependence on the Z/E-isomerism appear to be the Sp^2 atoms of the tri-substituted double bond (carbons a and c), and the α carbons of the alkyl substituents, including the methyl groups.

The largest difference between isomers, (differential shielding), is shown by carbon c, where the resonance in the Z-isomers occurs at a much lower field (125-126 p.p.m.) than in the E-isomers (122-123 p.p.m.). Conversely, carbon a - the position of alkyl substitution, resonates at higher fields in the Z-isomers compared to the E-isomers, though here the differences betwen the isomers are much smaller, in the order of 1 p.p.m. Higher field resonances are shown by the methyl group of the E-isomers, and by the α carbon atom of the substituents, R, of the Z-isomers. Figure 11 illustrates that the high field resonances occur when the α carbon atom is cis to the vinyl group.

Figure 11

Table 5: ^{13}C N.M.R. data of some Z and E-dienes, p.p.m. downfield from Me_4Si



C \ R	i-propyl		cyclopropyl		t-butyl	
	Z	E	Z	E	Z	E
a	145.03	145.12	139.12	139.99	146.35	147.30
b	132.51	133.60	132.88	133.27	134.74	134.11
c	125.07	123.17	126.83	123.97	126.63	122.10
d	114.47	114.66	114.44	114.07	115.27	115.15
CH_3	18.33	14.06	19.01	14.07	14.07	13.24
αC of R	34.73	36.91	12.88	19.07	36.01	36.37
βC of R	20.82	21.20	4.69	4.97	30.87	28.90

These results are in good agreement with those of Haan and van de Ven,[84,85] and other authors,[86,87] whose works have been concerned with the C.M.R. studies of di- and tri-substituted alkenes. As a general rule in ^{13}C N.M.R., chemical shifts of carbons in spatially crowded alkyl groups are more upfield than similar carbons in unperturbed systems.[88] This has been explained[89,90] by a 1,4 non-bonded (van der Waal's) interaction, causing partial polarisation in the C-H bonds and hence changes in the shieldings of the carbon atoms. The magnitude of the differential shielding will then be related to the number of hydrogens on each carbon and their relative spatial positions.

Very consistent values have been found for the differential shielding of allylic (α) carbons in Z and E-di-substituted alkenes, with the few discrepancies being tentatively explained[85] by assuming different rotational preferences (rotamers) of the side chains in some isomers. In tri-substituted alkenes these values are rather larger, probably as a consequence of steric interaction between geminal substituents. In all instances the workers found that the α carbons of Z-isomers were at higher fields, though the shieldings were not necessarily the same in both interacting groups. In conjugated systems (e.g. 1,3-pentadiene) it was shown that conjugation has little effect on the alkene part of the C.M.R., and that the best probe for structure determination was the α carbons - as confirmed by the present work.

Separation of the two 1,3-dienes obtained by dehydration of the cyclopropyl homoallylic alcohol (148) gave one isomer of shorter retention time and one of longer. The ^{13}C N.M.R. spectrum of the diene of shorter retention time was found to correspond with the data for the E-dienes, having the resonance of carbon c at 123.97 p.p.m. and the

methyl group at higher field than that of the other isomer. Thus, the cyclopropyl diene of longer retention time is the Z-isomer (131).

(iii) ^{1}H N.M.R.

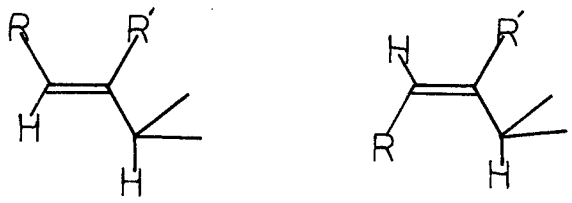
With the unambiguous identification of the 6 dienes described above, small changes in the ^{1}H N.M.R. spectra of these compounds can be correlated to the geometrical changes involved. Table 6 contains the ^{1}H N.M.R. data of several dienes, recorded at 100 MHz in CCl_4 solution.

Previous ^{1}H N.M.R. studies[91-93] on the structure determination of geometrical isomers of di- and tri-substituted ethylenes have yielded results that are in qualitative agreement with the conclusions reached in later C.M.R. studies.[85] However, it has been found that, in general, protons in a spatially crowded environment are deshielded, and that the differential deshieldings can be rather small and masked by overlapping peaks. Work by Frost[94] has shown the considerable deshielding of methine protons when cis to an alkyl substituent (Figure 12), and this has been verified by Bates[95] using similar model compounds (Figure 13).

Figure 12

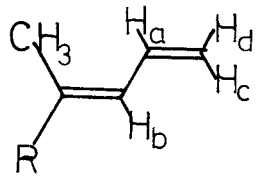
7.7 τ 7.37 τ

Figure 13



7.8 τ 7.2 τ

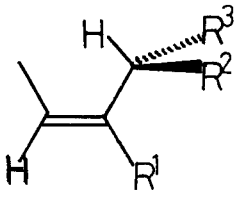
Table 6: ^1H N.M.R. data of some Z and E-dienes. Chemical shifts, τ, in p.p.m. (J values in Hz).



R \ H	CH_3	H_a	H_b	H_c & H_d	OF SUBSTITUENT R		
Z (32) ETHYL	8.27 (s)	3.56 (10.5, 17.0)	4.30 (10.5)	5.05 & 5.16 (10.5,17.0)	αCH_2 7.87 (7.5)q		βCH_3 8.97 (7.5,t)
E (38)	8.23 (s)	3.56 (10.5, 17.0)	4.26 (10.5)	5.05 & 5.16 (10.5,17.0)	7.95 (7.5)q		9.00 (7.5,t)
Z (127) i-PROPYL	8.39 (s)	3.47 (10.5, 17.0)	4.37 (10.5)	5.05 & 5.17 (10.5,17.0)	αC-H 7.06 (6.9)septet		βCH_3 9.06 (6.9,d)
E (128)	8.36 (s)	3.53 (10.5, 17.0)	4.23 (10.5)	5.02 & 5.14 (10.5,17.0)	7.79 (6.9)septet		9.03 (6.9,d)
Z (129) n-PROPYL	8.26 (s)	3.55 (10.5, 17.0)	4.24 (10.5)	5.05 & 5.16 (10.5,17.0)	αCH_2 7.90 (1.0, 7.0)	βCH_2 8.4-8.7 (c)	γCH_3 9.10 (7.0)
E (130)	8.24 (s)	3.55 (10.5, 17.0)	4.26 (10.5)	5.05 & 5.16 (10.5,17.0)	8.00 (7.0)	8.4-8.7 (c)	9.12 (7.0)
Z (131) CYCLOPROPYL	8.53 (s)	3.30 (10.5, 17.0)	4.18 (10.5)	5.04 & 5.15 (17.0,10.5)	αCH 8.15 (c)		Ring CH_2 9.3-9.6 (c)
E (132)	8.40 (s)	3.54 (10.5, 17.0)	4.21 (10.5)	5.04 & 5.15 (17.0,10.5)	8.24 (c)		9.3-9.6 (c)
Z (133) t-BUTYL	8.20 (s)	3.24 (10.5, 17.0)	4.28 (10.5)	4.98 & 5.07 (17.0,10.5)	t-butyl CH_3 8.81 (s)		
E (134)	8.26 (1.3)	3.54 (17.0, 10.5)	4.18 (1.3, 10.5)	4.98 & 5.07 (17.0,10.5)	8.92 (s)		

It was suggested that the difference between isomers was due to different rotamer populations, arising from non-bonded interactions between the i-propyl methyls and the vinyl R group in the Z conformation. The preferred rotamer for the Z isomer should be as illustrated in Figure 14, thus positioning the methine proton in a region of deshielding, due to the anisotropy of the double bond.

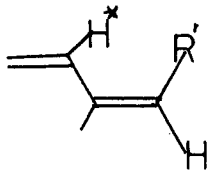
Figure 14



It is then to be expected that, as R^2 and R^3 are replaced by hydrogens, the rotamer distribution would change and deshielding decrease, until other factors predominated. Indeed it has been found[92] that deshielding is in the order of 0.5 p.p.m. for methine, 0.1 p.p.m. for methylene and -0.1 p.p.m. for methyl protons.

However, later work by Cárdenas,[96,97] on the deshielding of protons by alkyl groups in conjugated alkadienes, pointed to this deshielding being due to steric effects rather than double bond anisotropy (Figure 15).

Figure 15



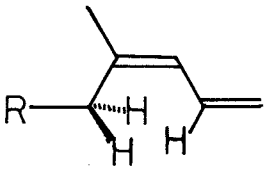
R' = Me, deshielding of H* = 0.55 p.p.m.

R' = t-Bu, deshielding of H* = 0.71 p.p.m.

The ^1H N.M.R. data presented in Table 6, for the 1,3-dienes of the present work, agrees well with the previous conclusions.

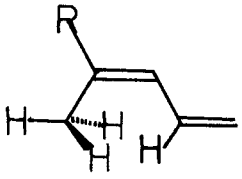
The vinyl proton H_a is seen to resonate in the region 3.53 - 3.56 τ for all E-isomers, and to be shifted downfield for most Z-isomers. This deshielding is largest for the t-butyl compound (0.34 p.p.m.), confirming the steric nature of the deshielding mechanism, and smaller for the cyclopropyl (0.24 p.p.m.) and i-propyl (0.06 p.p.m.) compounds as the steric interactions lessen. However, the ethyl and n-propyl compounds exhibit no difference between the E and Z-isomers - pointing to a preferred rotational distribution as shown in Figure 16, since the spatial environment of H_a is then very similar to that expected in all E-isomers (Figure 17).

Figure 16



R=Me,Et.

Figure 17



Unambiguous identification of the Z and E-isomers can be obtained from the α (allylic) proton resonances. Thus the methine proton of the i-propyl group is deshielded in the Z-isomer by 0.73 p.p.m. (in close agreement with the data of Figures 12 and 13),[94,95] though the cyclopropyl methine is deshielded by only 0.09 p.p.m. Similarly the ethyl and n-propyl α methylene groups are deshielded in the Z-isomers by 0.08 and 0.1 p.p.m. respectively, in good agreement with the data of Stehling[92] (see above).

In general the effect of the cis vinyl group on the methyl group resonances is again that of deshielding (in the order of 0.03 p.p.m.), the exception being that of the (E)-t-butyl compound which is shielded by 0.06 p.p.m.

Thus the data obtained from the 2 isomers of the n-propyl-1,3-dienes has been assigned as shown, the Z-isomer being eluted first by g.l.c.

Identification of the Z/E-isomers obtained from the pyrolyses of aromatic-substituted cyclobutenes

Samples of the aromatic-substituted cyclobutenes were pyrolysed at 180^{o} for approximately 20 minutes, by which time > 99% of the starting material had undergone isomerisation. The samples were analysed by g.l.c. (column E), all traces showing 2 product peaks only, attributable to the Z and E-dienes, with one peak of far greater retention time than the other.

The samples were re-pyrolysed, at 240^{o} for 1 hour, and re-analysed by g.l.c. All traces showed the presence of a third peak, of slightly greater retention time than the first peak, coupled with a drop in the percentage of the peak of longest retention time. Since only the E-isomer, in all cases, can undergo the 1,5-H shift expected at this temperature the product of longest retention time must be the E-diene.

This has been independently confirmed for the products obtained from 3-methyl-3-phenylcyclobutene (77), by synthesis of the Z and E-dienes and comparison of these with the pyrolysis products as described previously (page 47).

Identification of the Z/E-isomers obtained from the pyrolyses of 3-methyl-3-pentadeuteroethylcyclobutene (76)

Pyrolyses of the deuterated cyclobutene (76) gave 2 product peaks by g.l.c., whose areas were in the ratio 61:39, in order of elution. An authentic sample of 3-ethyl-3-methylcyclobutene (31) was pyrolysed at 180° and chromatographed under identical conditions, to also yield 2 product peaks - of identical retention times to the deuterated products. Since the Z-diene of the protio compound (32) was eluted first, it was concluded that the Z-isomer of the deuterated diene (135) was also eluted first - it being that isomer which amounted to 61% of the product.

Kinetic Measurements and Rate Studies

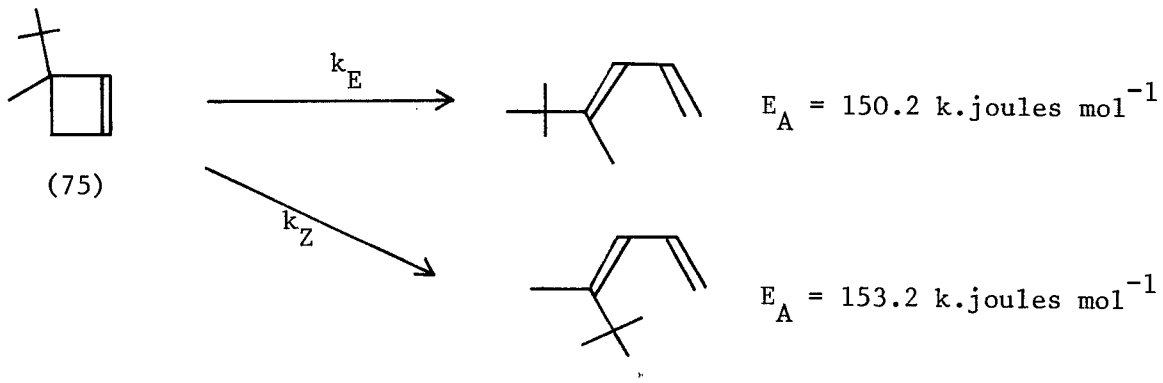
The kinetics of the isomerisations of the t-butyl methyl (75) and methyl phenyl (77) cyclobutenes were investigated, to correlate the results of the present work with previous data. The isomerisations were studied in the gas-phase over the temperature ranges shown, the rate of disappearance of starting material being measured by g.l.c. analysis. A plot of $\log_e(k)$ against 1/T gave a straight line for each compound, the data fitting the equations:

$$k_{t\text{-butyl}} = 10^{14.13} \exp(-(151.2 \pm 0.4)10^3/RT) \qquad (158\text{-}200^\circ)$$

$$k_{phenyl} = 10^{12.28} \exp(-(124.5 \pm 0.4)10^3/RT) \qquad (120\text{-}180^\circ)$$

The isomerisation of the t-butyl cyclobutene is seen to have a higher activation energy than that of the ethyl methyl cyclobutene (31) (see Table 1). The separate activation energies of formation of the two t-butyl dienes can be calculated by assuming a difference in energy similar to that between the two dienes of the ethyl compound (3.06 k.joules mol^{-1}), since both product ratios are similar, though reversed. Thus, though the Z-isomer is formed preferentially in the ethyl isomerisation, to the extent of 68%, the t-butyl isomerisation leads to 68% of the E-isomer (134), and hence has a lower activation energy, by 3.06 k.joules mol^{-1}, than the Z-isomer (Scheme 48).

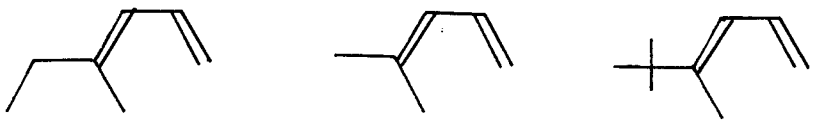
Scheme 48



(75)

The activation energy of formation of the E-diene (134) is found to be very similar to those of the other E-dienes, as shown in Figure 18.

Figure 18



E_A = 150.4 151.0 150.2 k.joules mol^{-1}

This can be attributed to the energy required to twist a methyl group into the plane of the ring, and is seen to be independent of the other alkyl substituent.

In a preliminary study, the rate of isomerisation of the phenyl cyclobutene (77) was found to be considerably faster than that of the t-butyl cyclobutene (75), and this is confirmed by the considerably lower activation energy and pre-exponential factor found from the rate study. The parameters obtained are in close accordance with the data of Brauman and other workers[15,34] for other phenyl-substituted cyclobutenes and again demonstrate the ability of the phenyl group to stabilise the concerted reaction, by approximately 25 k.joules mol^{-1} per phenyl substituent.

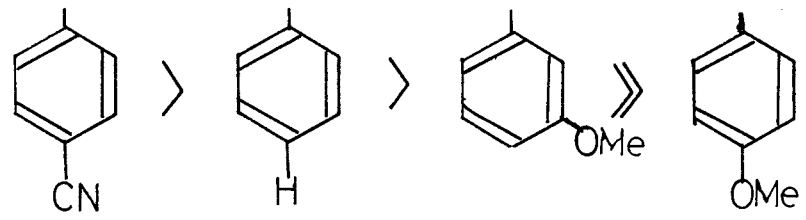
Semi-quantitative studies were performed on the other aromatic-substituted cyclobutenes prepared for the present work, such that a value of the half-life ($\tau_{\frac{1}{2}}$) of the isomerisation at a particular temperature was obtained. These values are shown in Table 7.

Table 7

R	T°C	$\tau_{\frac{1}{2}}$ sec
phenyl	180°	50
p-methoxyphenyl	180°	600
phenyl	161°	370
m-methoxyphenyl	161°	450
p-cyanophenyl	161°	280

Thus the rates of isomerisation of the cyclobutenes are in the order shown in Figure 19.

Figure 19



$k \times 10^4 \simeq$ 25 19 15.5 1.6 s^{-1}

It can be seen that the rates of isomerisation of the cyclobutenes depend to a great extent on the aromatic substituent, there being a factor of at least 10 times in the difference between the p-CN and p-OMe substituents. This order of reactivity closely resembles that of other, well documented aromatic reactions, such as the rates of dissociation of aromatic acids in water, with the exception that m-methoxy derivatives usually produce an increase in rate over the unsubstituted aromatic compounds.

These results appear to confirm the theory of Brauman,[15] discussed earlier, that the origin of the phenyl group stabilisation is the delocalisation of electron density from the termini of the π system onto the aromatic nucleus. Thus as the electron acceptor properties of the aromatic substituent increase (by the presence of an electron withdrawing substituent) the stabilisation, and hence reaction rate, should increase,

as is demonstrated by the p-cyano derivative. Conversely, electron donating substituents on the aromatic ring should decrease the rate, as is shown by the p-methoxy derivative.

Discussion of Pyrolysis Product Data

As indicated in Chapter 1, production of the Z-diene during the pyrolysis of unsymmetrically di-substituted cyclobutenes is considered unfavourable on steric grounds. The Z-dienes produced from cyclobutenes (72-80), see Tables 4 and 9, are certainly thermodynamically less stable than the E-isomers, since E-diene formation is always favoured during the dehydration of the corresponding homoallylic alcohols (146-150). Table 8 shows the relative ratios of the 1,3-dienes produced by the dehydration reaction.

Table 8: Relative ratios of Z:E-1,3-dienes produced by dehydration

R	Z%	E%	A value (kjoule mol^{-1})
methyl	-	-	7.1
ethyl	-	-	7.6
n-propyl	40	60	8.8
i-propyl	36	64	8.8
cyclopropyl	51	49	-
t-butyl	0	100	23.5
phenyl	22	78	13.0

A measure of the steric size of the substituent R can be obtained from the A value,[98-100] or conformational free energy difference, also shown in Table 8. The absolute values apply only to the axial/equatorial equilibrium for cyclohexane, though a comparison of the figures is valid for these arguments. The A value for cyclopropyl has apparently not been reported, though the product ratio in Table 8, of almost 50:50, would indicate an effective value similar to that of methyl.

The isomerisations of the t-butyl, cyclopropyl and aromatic-substituted cyclobutenes are seen to produce the E-dienes as major products, though this is still considered anomalous since the amounts of Z-dienes produced far exceeds that expected on steric grounds. The amounts of Z-dienes expected, on steric grounds alone, can be estimated from δA, the difference between the A values of the substituent, R, and methyl ($\delta A = A_R - A_{CH_3}$). By making the difference in activation energy of the Z and E-dienes equal to δA (k.joules mol^{-1}), the expected Z/E ratios for the cyclobutene isomerisations have been calculated at 180^{o} and appear in Table 9, together with the observed values.

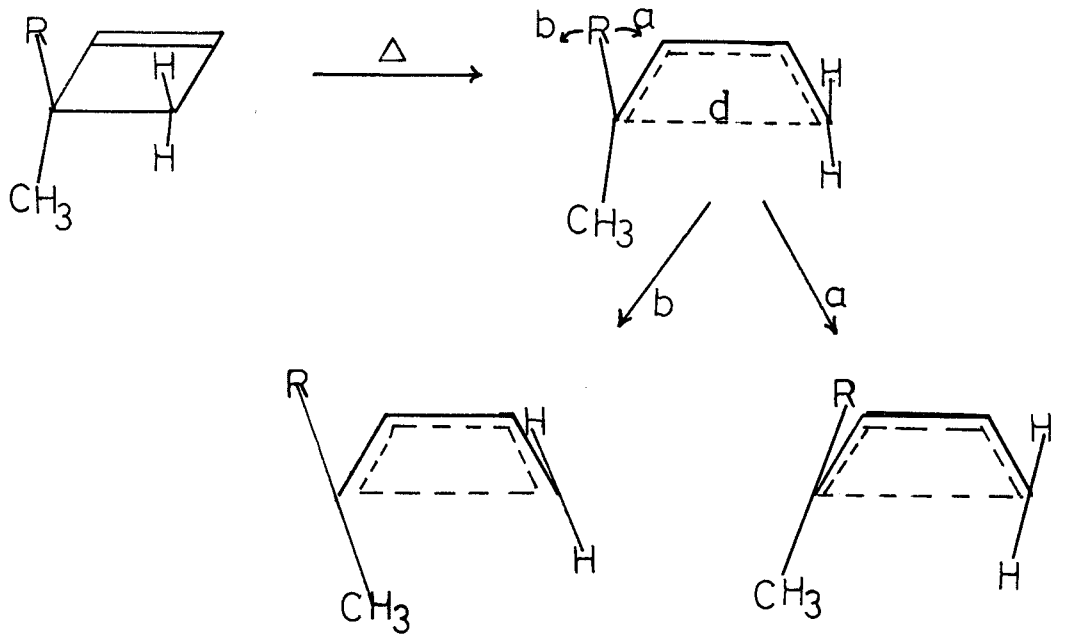
Table 9

R	δA k.joule mol^{-1}	Expected Z/E	Observed Z/E
ethyl	0.5	47/53	68/32
n-propyl	1.7	39/61	62/38
i-propyl	1.7	39/61	65.5/34.5
cyclopropyl	-	-	43/57
t-butyl	16.4	1/99	32/68
phenyl	5.9	17/83	30/70

Thus some effect (or effects) must be occurring to counterbalance, and in certain cases overcome, the steric interactions present. Earlier considerations on benzocyclobutenes (Chapter 1) have shown the importance of electronic effects upon these electrocyclic reactions, and it is reasonable to predict that these electronic effects could favour the production of the Z-isomers.

Several interactions can be postulated to be present, during the isomerisations of the cyclobutenes, that would fulfil the requirements for the Z-isomer production and these are described below. These interactions are mostly considered to be occurring at the transition state of the isomerisation. After the work of Hsu,[5] described earlier, the transition state is considered as being that point where, after an initial stretching of the 3-4 bond to an intermediate distance d, the carbon atoms 3 and 4 start to rotate in a conrotatory manner as shown in Scheme 49.

Scheme 49

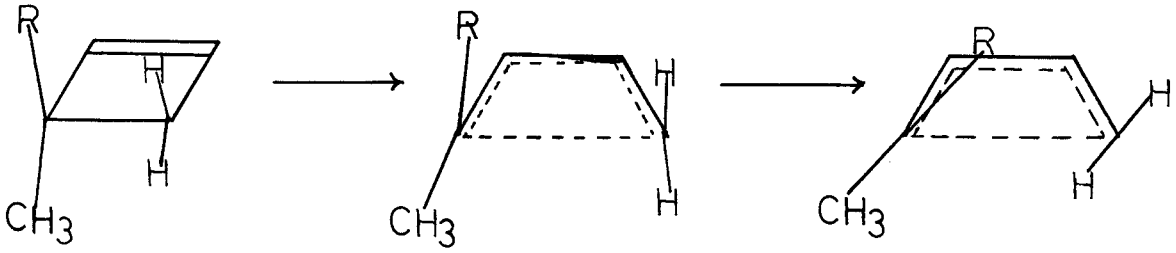


(i) The original hypothesis,[28] concerning the isomerisation of 3-ethyl-3-methylcyclobutene (31) and describing an interaction between the terminal hydrogens of the ethyl substituent and the double bond (Chapter 1, Figure 3), can still apply to the isomerisation of the alkyl-substituted cyclobutenes investigated. Thus the n-propyl, i-propyl and t-butyl substituents each possess a greater number of hydrogens than ethyl that can adopt a position suitable for interaction with the double bond. This increases the probability of such an interaction, which should lead to an even greater tendency for Z-isomer formation than for the ethyl substituent. This would be offset by the increased size of the substituent relative to ethyl, producing the sort of product ratios as observed in Table 4. Less interaction is to be expected for the cyclopropyl substituent with correspondingly less Z-isomer produced, as is also observed.

This mechanism is supported by the N.M.R. data of some of the cyclobutenes studied. In certain examples (R = n-propyl, i-propyl, cyclopropyl and t-butyl) the cyclobutene ring has been shown to be twisted, with the R substituent in a "pseudo-axial" conformation, as described earlier. This places the R group in a very favourable position, with the terminal hydrogens able to come into close proximity to the double bond region. However, the mechanism is unable to account for Z-isomer formation in the aromatic-substituted compounds, since these have no hydrogens in a suitable position for interaction. Similarly, the pentadeuteroethyl derivative, also having no hydrogens in a suitable position, would be expected to yield a product ratio very different from that of the hydrogen analogue, though in practice the amounts of Z-dienes produced are similar (61:68% respectively).

(ii) The cyclobutene isomerisation has been previously studied[101,102] using the Principle of Least Motion,[103] successfully explaining the conrotatory movement of the methylene groups. Application of the general principle, that reactions will be favoured that involve the least change in atomic position, to the situation of the 3,3-disubstituted cyclobutenes implies that the bulkier group, during the stretching of the 3-4 bond, would tend to lag behind and thus adopt a position suitable for Z-isomer formation (Figure 20).

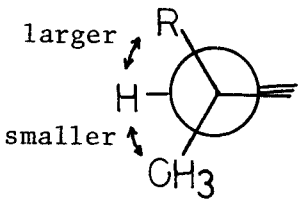
Figure 20



However, this mechanism is unable to explain the differences occurring in the aromatic-substituted series, since pMeO-phenyl produces 52% and m-MeO-phenyl 32% of the corresponding Z-isomers, where no difference between them would be expected. Also the isomerisation of 3-methylcyclobutene (19), R = H, should produce some Z-diene product though none is detected in the product.

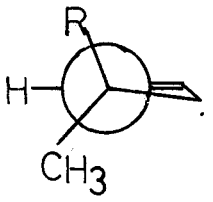
(iii) A Newman diagram (Figure 21) of the 2-3 bond of the cyclobutenes shows the relationship of the substituents, R and CH_3, to the adjacent olefinic proton.

Figure 21



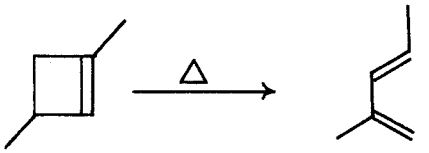
Since R > CH_3, the rotational barrier will be greater for R eclipsing with H than for CH_3 eclipsing with H, thus favouring the turning of the R substituent into the plane of the ring to give the Z-product. The NMR data noted previously also fits in well with this argument, since the greater R-H repulsion would tend to twist the ring so that R adopted the axial conformation (Figure 22).

Figure 22

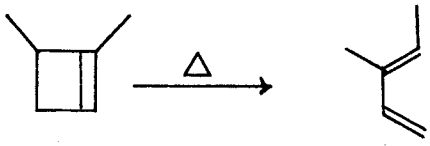


Again, this eclipsing effect does not explain fully the differences in the aromatic series of compounds, though a simple test of this model would be the isomerisation of a 2-methyl-3,3-disubstituted cyclobutene, where Z-product formation should be enhanced by the larger rotational barrier between the olefinic CH_3 and R substituent. Confirmation of this increased rotational barrier comes from the activation energies (E_A) of isomerisation of 1,3- and 1,4-dimethylcyclobutenes[20] as shown in Scheme 50.

Scheme 50



E_A = 138.3 k.joule mol^{-1}



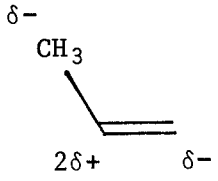
E_A = 139.9 k.joule mol^{-1}

The 1.6 k.joule mol^{-1} difference in E_A is accounted for by this difference between the CH_3-H and CH_3-CH_3 repulsion.

(iv) Electronic effects

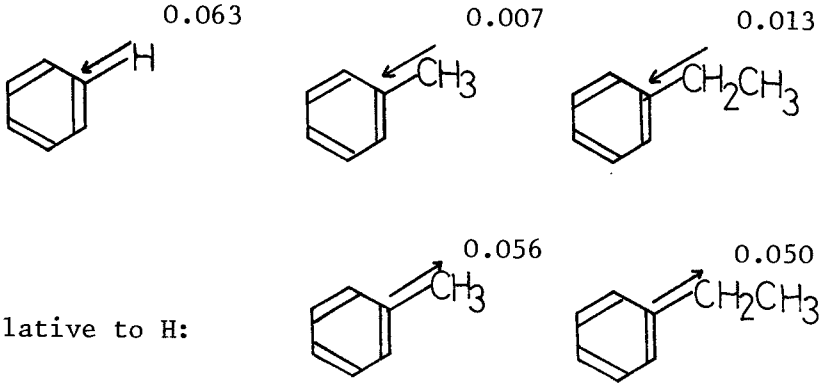
Recent calculations[104] have attempted to show the substituent effects of a methyl group on alkene and benzene substrates, in terms of charge transfer and polarisation. In propylene (Figure 23) little net transfer of electrons from the methyl to the ethylene was found, though a significant polarisation of the π electron system was shown to occur making the terminal CH_2 rather negative. This can be considered as having arisen from a negative charge associated with the methyl group repelling electronic charge along the system to the terminus.

Figure 23



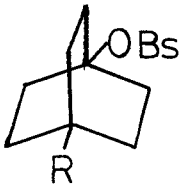
Other calculations,[105] on the charge distribution in mono-substituted benzenes, have given figures for the σ electron flow associated with various substituents. For methyl, although there is a slight transfer of electrons to the benzene from the methyl group, compared to hydrogen there is a relative δ- associated with the methyl group, as shown in Figure 24. The effect of the ethyl group in this context is slightly larger (more electron donation), thus making it slightly less δ-.

Figure 24



Solvolysis data for a series of bicylooctyl brosylates[106] shows the effect of the transition Me ⟶ t-Bu upon the reaction rate (Figure 25).

Figure 25



Solvolysis in acetic acid, 75°

R	k_R / k_H
t-Bu	0.55
i-Pr	0.43
Et	0.36
Me	0.30

The authors argue that the results confirm the electron donating power of the alkyl substituents, with the relative donating power in the order tBu > i-Propyl > etc. as expected.

The above results indicate that the amount of negative charge associated with the alkyl substituents, R, will decrease in the order shown in Scheme 51.

Scheme 51

Me > Et > i-Pr > t-Bu

$\delta-$ ⟶ smaller

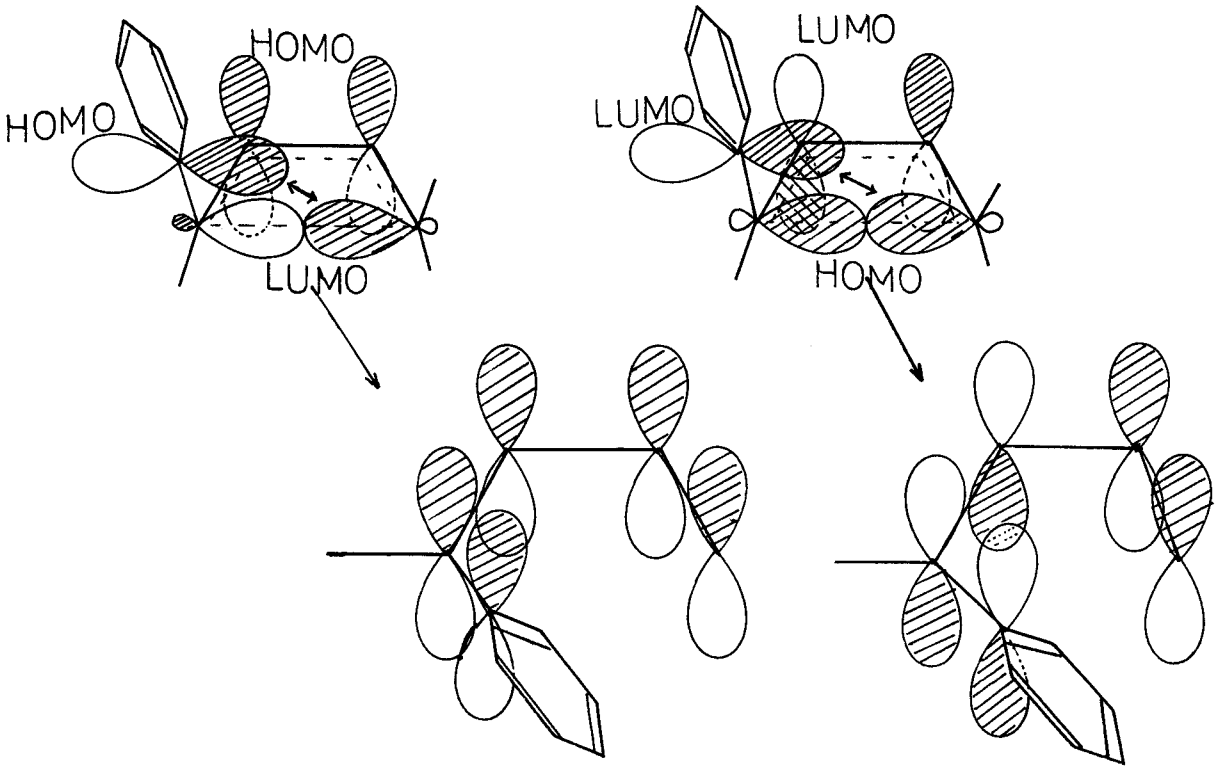
Consideration of the transition state of the isomerisation of the cyclobutenes shows that there will be a repulsive interaction between the $\delta-$ charge of the substituents, R and CH_3, and the terminus of the newly-forming diene, due to the coulombic repulsion of two electron-rich centres. Consequently, the larger $\delta-$ charge associated with the substituent, the greater the repulsion; since CH_3 has the largest $\delta-$ this will always tend to move away from the diene terminus, relative to the other alkyl substituent. This directly favours the production of the Z-diene, though it is offset for the larger substituents by the steric effects present.

No accurate data is available for the position of cyclopropyl in the sequence obtained above (Scheme 51). However, the type of bonding in cyclopropane, and the ring-current associated with it, would point to the substituent possessing an electron rich ($\delta-$) character, probably more so than methyl, thus favouring the E-isomer as is observed (57% E

produced by pyrolysis). Similarly no data is available for the pentadeuteroethyl substituent. The size of this group is expected to be slightly smaller than its hydrogen analogue, which would favour Z-diene formation compared to ethyl. Electronic effects must be important, the C_2D_5 moiety having to possess a higher $\delta-$ charge associated with it (than ethyl) to produce the observed product ratio of 61% Z-diene:39% E-diene.

For the aromatic substituents, R, the interaction at the transition state will be different. There now exists, at the 1- position of the aromatic nucleus, a molecular orbital that is capable of, and in a suitable position for, interacting with the breaking 3-4 bond of the cyclobutene. This will be an attractive HOMO-LUMO interaction, in the form of a 1,2 shift (suprafacially allowed), though no actual bond formation would occur (Figure 26). This will tend to pull the aromatic ring into the plane of the cylobutene, giving rise to the Z-product.

Figure 26



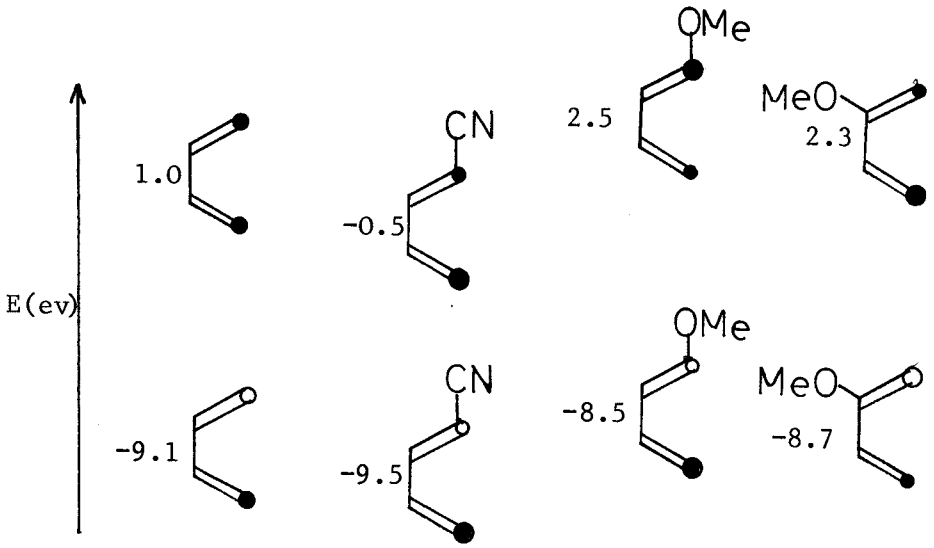
Molecular orbital theory predicts that the extent of the interaction (Δ) will be proportional to the square of the orbital coefficients, and inversely proportional to the energy level difference between the HOMO and LUMO, as shown in Figure 27.

Figure 27

$$\Delta \propto \frac{c_1 c_2^2}{E_{LUMO} - E_{HOMO}}$$

The orbital interactions ($HOMO_{AROMATIC}$-$LUMO_{DIENE}$ $\underline{OR}$ $LUMO_{AROMATIC}$-$HOMO_{DIENE}$) will thus be determined by the energy level differences - the smaller the difference the greater the interaction. The size of the interaction (and hence amount of Z-isomer produced) will also depend on the size of the coefficient of the aromatic orbital considered, which in turn will depend upon the substituents present on the aromatic ring. Both the energy level differences and orbital coefficients can be obtained from the work of Houk[107] on the frontier orbitals of alkenes and dienes. His calculations

Figure 28



on both coefficient size and orbital energy levels are in good agreement with qualitative considerations, and are depicted for the relevant compounds in Figure 28, the size of the coefficients being proportional to the size of the circle drawn at that position. For this work the 1-substituted butadienes can be considered as also equivalent to the p-substituted benzenes, and the 2-substituted compound as equivalent to m-substituted benzene. From Figure 28 it can be seen that the preferred HOMO-LUMO interactions (i.e. those with the smallest energy differences) will be:

(a) for p-MeO- : $HOMO_{AROMATIC} - LUMO_{DIENE}$

(b) for p-CN- : $LUMO_{AROMATIC} - HOMO_{DIENE}$

(c) for m-MeO- : $HOMO_{AROMATIC} - LUMO_{DIENE}$

Considering now the relevant, interacting molecular orbital of the aromatic species, the size of the orbital coefficients at the 1-position for the above compounds (and hence amount of Z-diene expected) are in the order:

p-MeO- > p-CN- > phenyl > m-MeO-

This is in good agreement with the observed order of Z-diene production:

p-MeO- > p-CN- > m-MeO- $\geq$ phenyl

% Z-product	52	45	32	30

That the m-MeO derivative yields slightly more Z-diene than expected from the above arguments is probably due to the degree of inaccuracy inherent in these arguments.

Furthermore, the observed change in rate of isomerisation of the aromatic-substituted cyclobutenes can be explained in terms of these

molecular orbital arguments. The observed rate order (Figure 19 and Table 7):

p-CN- > phenyl > m-MeO- > p-MeO-

faster ⟶ slower

is seen to follow exactly the order of the energy level of the LUMO of the aromatic species:

	p-CN- ,	phenyl ,	m-MeO ,	p-MeO
Energy of LUMO (e.v.)	-0.5	1.0	2.3	2.5

This again confirms the hypothesis of Brauman that the stabilisation of the aromatic substituent arises from its ability to accept electrons from the diene terminus, since the lower the energy of the LUMO of the aromatic substituent the stronger the interaction and more electron delocalisation onto the aromatic species.

Thus, in general, it can be postulated that any electron-rich species will experience a repulsive interaction with the remote diene terminus, and conversely an electron-deficient species (or one possessing suitable acceptor properties) will experience an attractive interaction.

This can be used to rationalise the data obtained from the benzocyclobutenol isomerisations outlined in Chapter 1. The hydroxyl substituent (see Scheme 12), possessing a lone pair, will be extremely electron-rich and so be strongly repelled to give solely the E-product. Conversely, the positive charged nitrogen of the compound (68) will be attracted towards the plane of the ring, to give only Z-product, as observed in Scheme 20.

CHAPTER 3

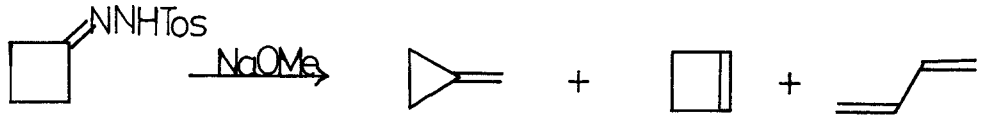
REARRANGEMENTS OF CYCLOBUTYLIDENES

Introduction

The formation of cyclobutylidenes has been accomplished using the Bamford-Stevens[109] decomposition of the cyclobutanone tosylhydrazones with base.

Cyclobutylidene[66] itself rearranges primarily to methylenecyclopropane (125), Scheme 31, though a minor quantity of cyclobutene (13) is produced by an intramolecular 1,2-hydrogen shift. Trace quantities of butadiene (14) probably originate from the thermal decomposition of the cyclobutene.

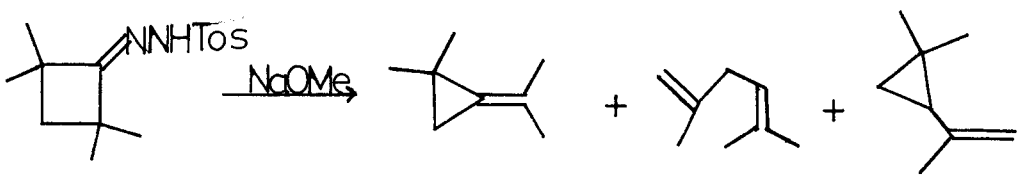
Scheme 31



(124) (125) 80% (13) 19% (14) 1%

Substitution of the ring by 4 methyl groups leads to little change in the product composition[110] (Scheme 52), with products (174) and (175) being

Scheme 52

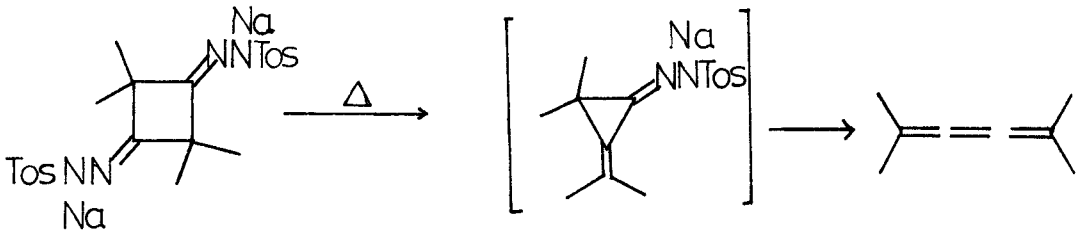


(172) (173) (174) (175)

obtained in varying amounts.

Careful pyrolysis of the dry sodium (or lithium) salts of tosylhydrazones also produces the corresponding carbenes. Thus, the disodium salt of the ditosylhydrazone (176)[111,112] shown in Scheme 53 yields the intermediate methylenecyclopropane (177), which decomposes further to the butatriene (178).

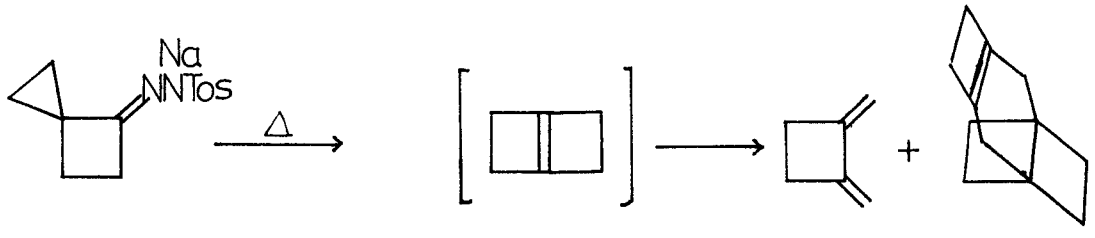
Scheme 53



(176) (177) (178)

The spiro compound (179),[113,114] on pyrolysis, gave the ring-expanded product (180), shown in Scheme 54. This is as expected for the rearrangement of the cyclopropyl carbene (see Chapter 2), this taking preference over the cyclobutylidene rearrangement.

Scheme 54

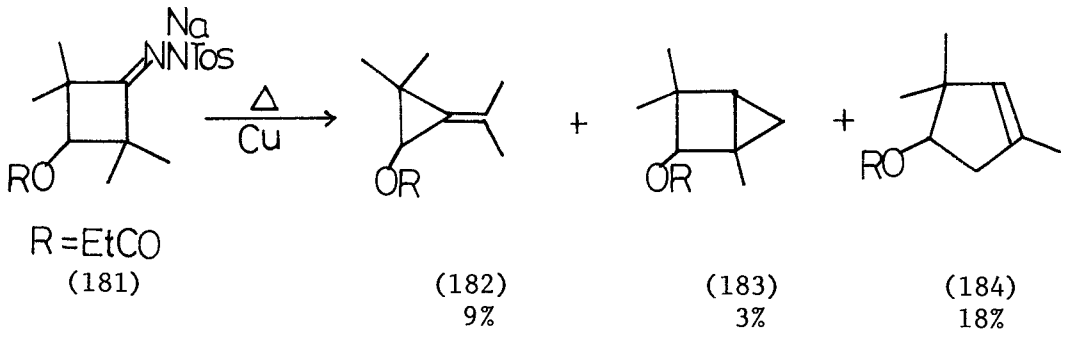


stable at -20^{o}

(179) (80)

Major studies[115-117] have occurred for the more-substituted monocyclic derivatives, after the incorrect assignment of structure (182) to the pheromone of the American Cockroach. The compound was prepared, after several unsuccessful attempts, in small quantities by the pyrolysis of the sodium salt of the corresponding cyclobutanone tosylhydrazone (181) with copper,[117] as illustrated in Scheme 55.

Scheme 55

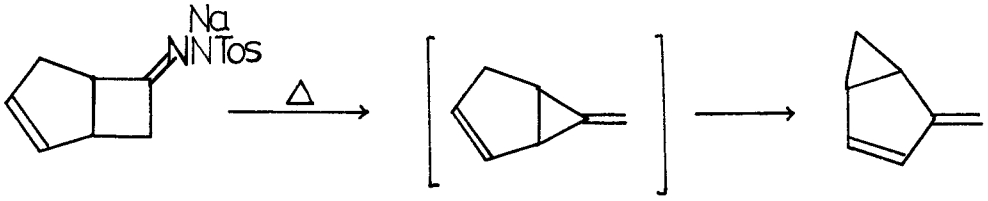


(181) (182) 9% (183) 3% (184) 18%

Pyrolyses and photolyses of the compound (181) in solution were less successful, yielding complex mixtures and none of the desired product (182).

Bicyclic systems (185) have produced routes to the homofulvene system (187).[118] The initially formed methylenecyclopropane (186) undergoes a vinylcyclopropane rearrangement to give the product (187).

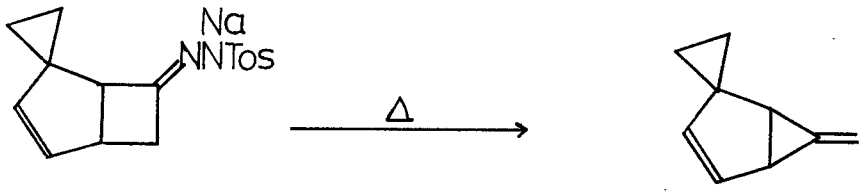
Scheme 56



(185) (186) (187)

The presence of a spiro-cyclopropyl substituent (188) has enabled the methylenecyclopropane (187) to be isolated (Scheme 57).[118]

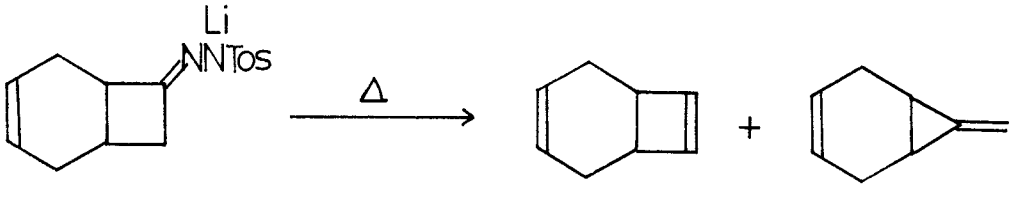
Scheme 57



(188) (189)

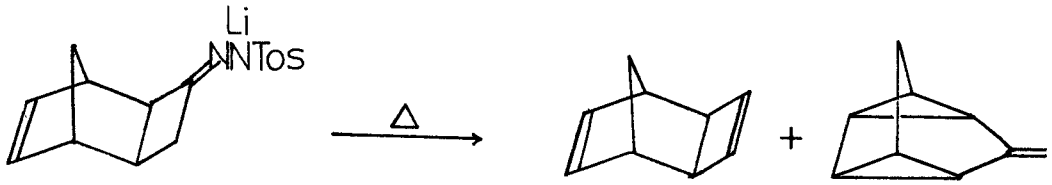
The effects of additional fused rings on the available reaction pathways of cyclobutylidenes has been further investigated (Scheme 58).[119] Methylenecyclopropanes and cyclobutenes are formed generally, though further rearrangement of the products was found to occur (Schemes 59, 60).

Scheme 58

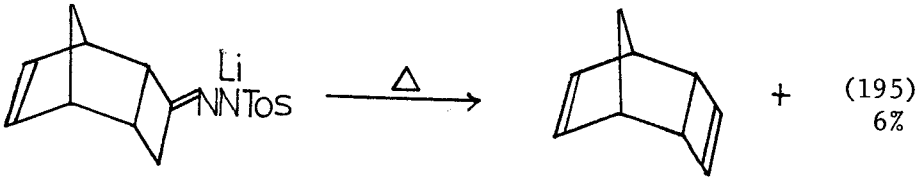


(190) (191) 3% (192) 9%

Scheme 59

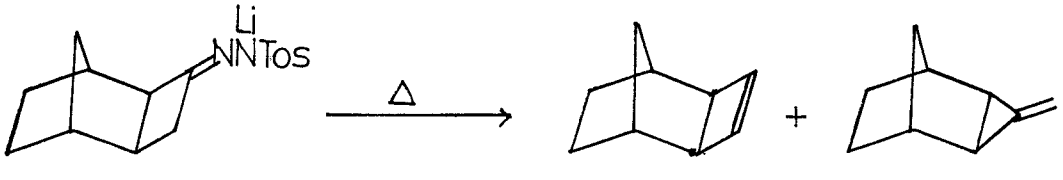


(193) (194) 3% (195) 6%

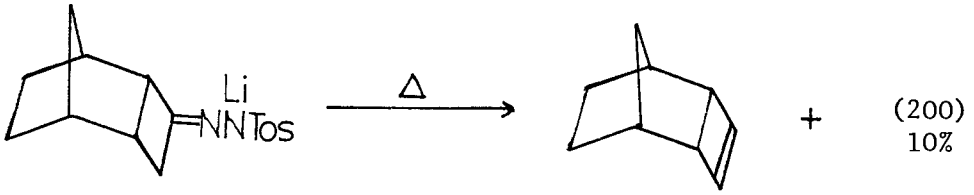


(196) (197) 3% (195) 6%

Scheme 60



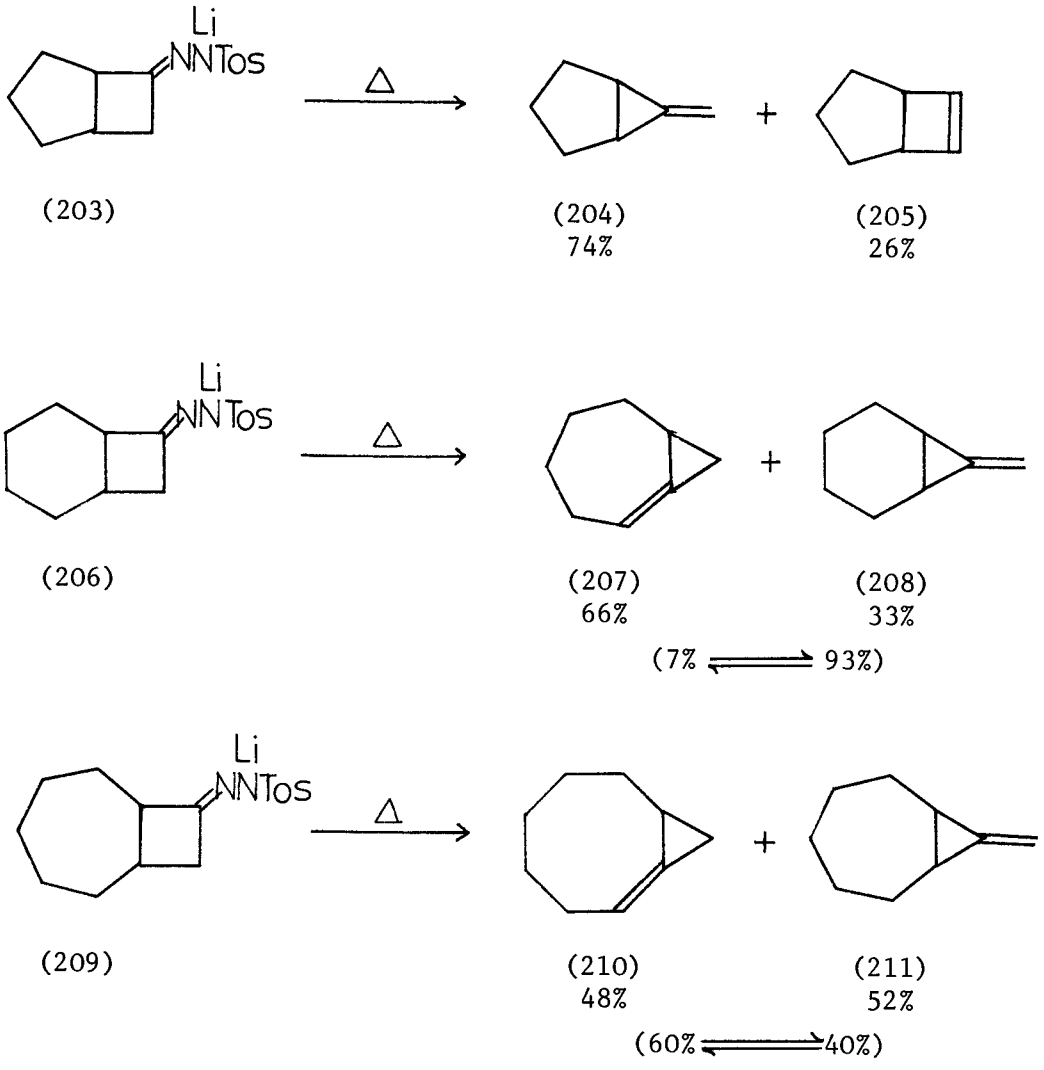
(198) (199) 3% (200) 10%



(201) (202) 3% (200) 10%

The formation of the exo methylenecyclopropane (200) from both the exo (198) and endo (201) compounds is probably a result of the equilibration of the exo/endo methylenecyclopropanes to give the thermodynamically more stable isomer (200). Further work[120] on saturated fused systems has again shown the establishment of an equilibrium between certain isomeric, fused methylenecyclopropanes (Scheme 61).

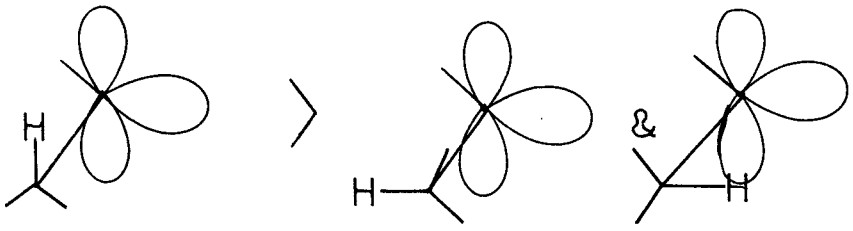
Scheme 61



The percentages in brackets show the composition of the thermodynamic equilibria established between the isomers, at 180°. The results are interpreted[120] as suggesting that the more-substituted σ-bond migrates preferentially during the pyrolyses.

The 1,2-hydrogen shifts observed during some of the thermal decompositions have been shown to depend upon the geometry of the migrating hydrogen.[121] The ease of rearrangement is greatest for a hydrogen in the perpendicular orientation as opposed to the syn- or anti-planar orientations (Figure 29).

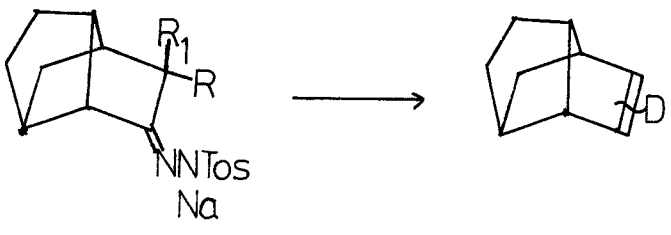
Figure 29



PERPENDICULAR

For this work, the rigid molecule (212) was utilised, specifically deuterated at the positions shown in Scheme 62. It was established that the exo atom migrated, with an exo/endo ratio of 138:1.

Scheme 62



For R = H, R_1 = D

R = D, R_1 = H

R = R_1 = H

(212) (213)

The lack of data on the lesser-substituted cyclobutylidenes, and the ready availability of the precursors, prompted the present study.

Results and Discussion

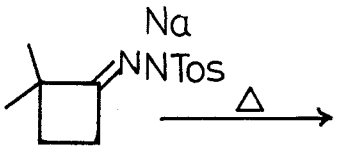
Schemes 63 - 68 show the results of the carbenoid decompositions of the tosylhydrazones studied in the present work. The decompositions were performed by pyrolysis, at 140^{o}, of the dry sodium salts of the tosylhydrazones, using 3 different modifications:

(a) Vacuum pyrolysis in a sealed Pyrex tube,

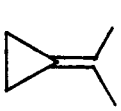
(b) Vacuum pyrolysis in a Pyrex tube, with a slow dry N_2 bleed into a -78^{o} trap

and (c) Vacuum pyrolysis in the presence of Copper, with N_2 bleed into a -78^{o} trap.

Scheme 63

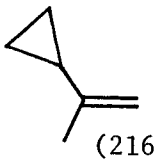


(214)



(215)
53%

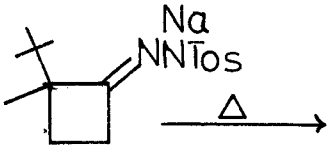
+



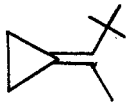
(216)
47%

Method (a)

Scheme 64

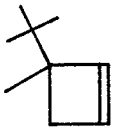


(217)



(218)
99%

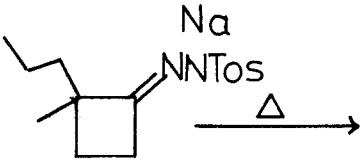
+



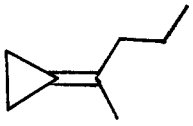
(75)
1%

Method (a)

Scheme 65

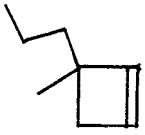


(219)



(220)
98%

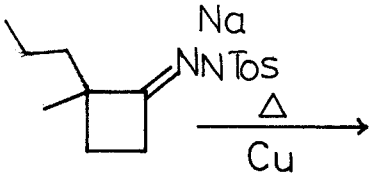
+



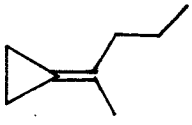
(73)
1%

Method (a & b)

Scheme 66

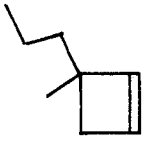


(218)



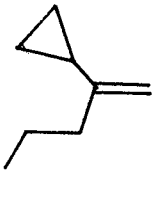
(220)
66%

+



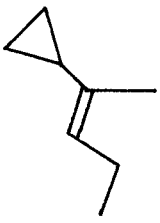
(73)
7%

+



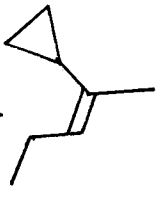
(221)
7%

+

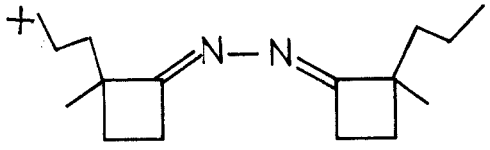


(222)

+



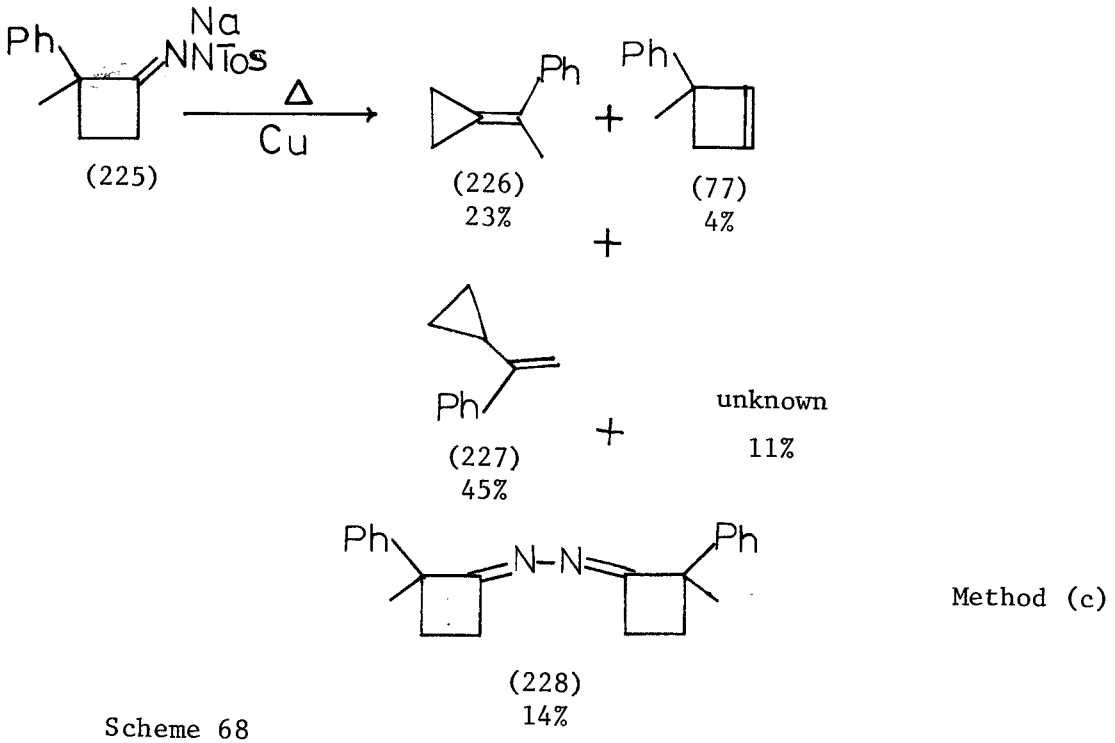
(233)
4%



(224)
10%

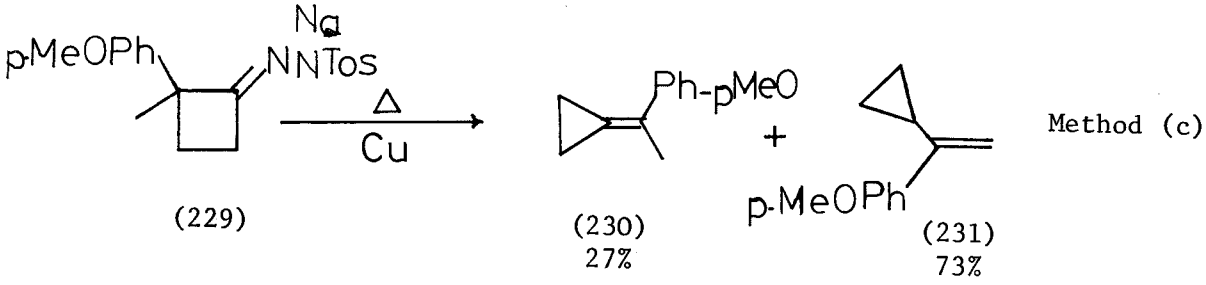
Method (c)

Scheme 67



Method (c)

Scheme 68

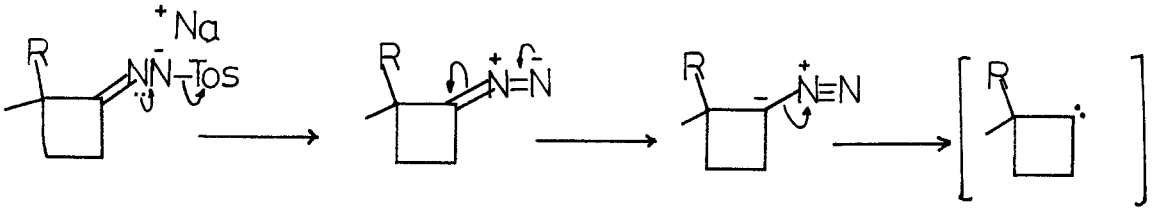


Method (c)

The presence of copper, during the pyrolyses, has been found to increase the overall yield of the decompositions (70-98%), though with an attendant increase in the amount of azine and further-rearranged products. The decomposition of the tosylhydrazone anion occurs via the mechanism shown in Scheme 69, the increased yields with copper being due to its catalytic effect on the decomposition of the intermediate diazo compound,[122] as discussed previously in Chapter 2.

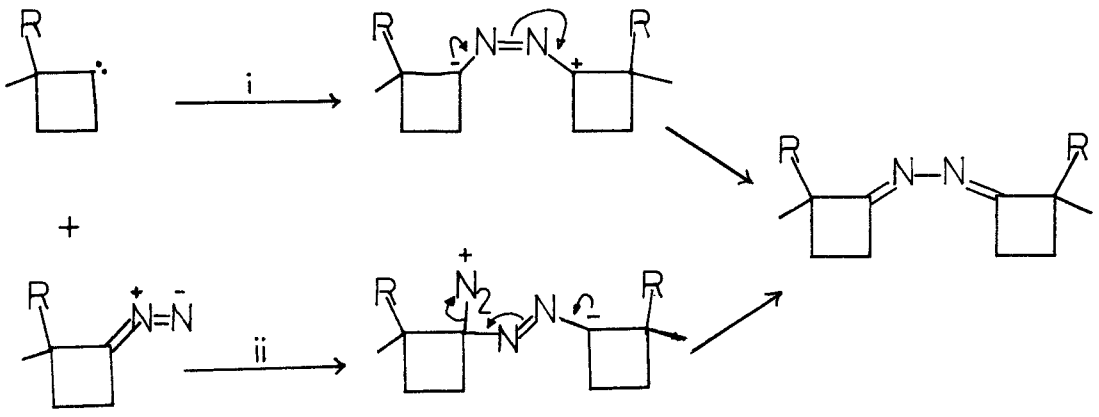
The production of azine during the decomposition can be postulated to occur via two mechanisms, (i) attack of the carbene on the intermediate diazo compound or (ii) a bimolecular reaction between two

Scheme 69



molecules of diazo compound, (Scheme 70).

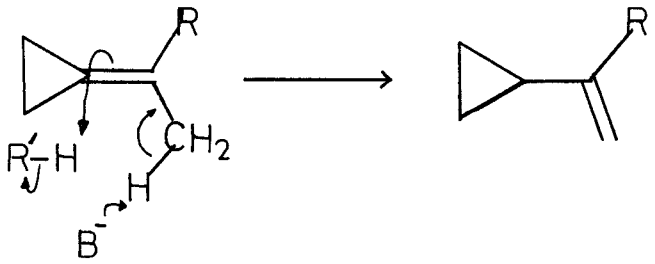
Scheme 70



Schemes 63-66 show that the alkyl-substituted cyclobutylidenes rearrange to give the methylenecyclopropanes as major products, as expected. It would appear that the size of the alkyl substituent, R, determines the proportion of the methylenecyclopropane produced, since R = n-propyl and R = t-butyl yield approximately 98% whereas R = Me yields only 53% of the methylenecyclopropanes, under the same conditions of decomposition.

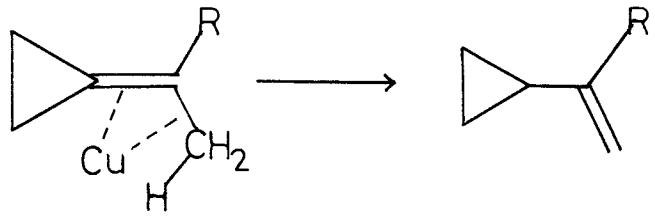
That the mode of decomposition of the tosylhydrazones affects the product composition can be seen from a comparison of Schemes 65 and 66. The greater variety of products formed when copper is present also coincides with the far greater yield as described previously. Under these conditions, large amounts of vinylcyclopropanes are produced, by the migration of all possible hydrogens α to the double bond. The formation of the vinylcyclopropanes can be considered to occur by several mechanisms, though almost certainly from the further rearrangement of the methylenecyclopropanes, as shown in Schemes 71, 72.

Scheme 71



Scheme 71 illustrates the abstraction of the α hydrogen by base, B^-, present as the tosyl anion, or the tosylhydrazone anion itself.

Scheme 72



Scheme 72 shows formation of the vinylcyclopropane via a copper/alkene complex (see Chapter 2) - in which a 1,3-hydrogen shift will be suprafacially allowed. The vinylcyclopropanes are formed as major products from the decomposition of the aromatic-substituted cyclobutylidenes (Schemes 67, 68).

The 1,2-hydrogen shift is seen in several of the decompositions (Schemes 64-67) as expected, in the form of the cyclobutenes, though only as minor products. The presence of substituents on the cyclobutylidene ring thus reduces the amount of the 1,2-hydrogen shift occurring, relative to cyclobutylidene itself, perhaps as a result of unfavourable geometries. However, no 1,2-alkyl migration has been observed in the present work, nor the γ-C-H insertion reaction that has been detected in some previous work (Scheme 55, (183)).

CHAPTER 4

EXPERIMENTAL

Infra-Red (I.R.) spectra were recorded on either a Perkin-Elmer 157G or Pye-Unicam SP200 spectrophotometer. Solid samples were run as Nujol mulls and liquids as thin films or in carbontetrachloride (CCl_4) solution. Absorptions are quoted in wavenumbers (cm^{-1}) and the following abbreviations have been used: s (strong), m (medium), w (weak).

Proton Magnetic Resonance (P.M.R.) spectra were recorded in CCl_4 solution, unless otherwise stated, at 60 MHz on a Perkin-Elmer R12 spectrometer or at 100 MHz on a Varian HA100 instrument. Chemical shifts are quoted on the τ scale, relative to Me_4Si as internal standard at 10.00 τ.

Carbon Magnetic Resonance (C.M.R.) spectra were recorded on either a Bruker HFX90E or a Varian XL100 instrument. Abbreviations used are: s (singlet), d (doublet), t (triplet), q (quartet), c (complex).

Mass Spectra (M.S.) were recorded using an A.E.I. M.S.12 spectrometer.

Analyses by gas-liquid chromatography (g.l.c.) were carried out using a Perkin-Elmer F11 chromatograph equipped with a flame ionisation detector and using nitrogen as carrier gas. Peak areas were measured using a Disc integrator where possible, or standard graphical techniques where not.

Preparative g.l.c. was accomplished using an Aerograph A700 instrument equipped with a katharometer and using hydrogen as carrier

gas. The columns used for g.l.c. are listed below together with their abbreviations as used in the text:

Column A: 2 metre × 3 mm, 10% Carbowax 20M on Chromosorb W

Column B: 2 metre × 3 mm, 20% 1,3 D.C.E.P. on Phasesep P

Column C: 4 metre × 3 mm, 15% P.P.G. on Chromosorb W

Column D: 4 metre × 3 mm, 15% P.P.G.A. on Chromosorb W

Column E: 1 metre × 3 mm, 15% P.P.G. on Diatomite

Column F: 3.5 metre × 9 mm, 10% Carbowax 20M on Chromosorb W

Column G: 3.5 metre × 9 mm, 20% 1,3 D.C.E.P. on Phasesep P

Melting points (m.p.) are uncorrected

Preparation of 3-t-butyl-3-methylcyclobut-1-ene

(i) Pivalic acid (81), (107.5 g), was esterified with methanol (100 g) and conc. sulphuric acid (5 g) according to the method of Vogel.[123]

Yield: 85.1 g (70%), b.p. 102°

I.R. 2980 (s), 1730 (s), 1160 (s)

P.M.R. (neat liquid) 6.41 (s,3H), 8.83 (s,9H)

(ii) Methyl magnesium iodide (2.6 mole) was prepared according to Vogel.[123] Methyl pivalate (82), (148.5 g), was added in dry ether and the reaction mixture worked up with saturated ammonium chloride solution and ice. The product was distilled under vacuum to give a white, crystalline solid.

Yield: 126 g (85%) m.p. 72-73° b.p. 48° at 25 torr

I.R. 3350 (s), 1380 (s), 1150 (s)

P.M.R. 8.86 (s,6H), 9.07 (s,9H)

(iii) 2,3,3-Trimethylbutan-2-ol (83), (126 g), was dehydrated by fractional distillation with conc. sulphuric acid (20 ml) and water (25 ml).

Yield: 78.4 g (74%) b.p. 78^{o}

I.R. 2950 (s), 1640 (m), 895 (s)

P.M.R. 5.37 (c, 2H, J_{gem}= 0.5 Hz, J_{allyl}= 1.3 Hz), 8.28 (s, 3H, broad), 9.95 (s, 9H)

(iv) Ethyl diazoacetate was prepared from glycine ethyl ester hydrochloride as described in Organic Syntheses.[124] Trimethyl phosphite: copper(I) iodide catalyst was prepared according to the method of Peace.[49] Addition of the diazo compound to the alkene (84) was carried out essentially as described by Peace and Wulfmann.[49]

2,3,3-Trimethylbut-1-ene (84), (15.8 g), copper catalyst (0.26 g) and "Vazo" (0.02 g) were refluxed in a 3-neck flask on a steam bath, and a mixture of the alkene (84), (15.8 g), and ethyl diazoacetate (13.4 g) was added at a rate of 6 drops per minute. The contents of the flask rapidly turned dark-brown with the evolution of nitrogen. After the addition, the mixture was refluxed for 24 hours. Excess alkene (21.5 g) was distilled at 20 torr from the reaction mixture into a -78^{o} trap, followed by distillation, at 0.1 torr, of the product (11.65 g) into another -78^{o} trap (acetone/dry ice bath)

P.M.R. analysis showed the product to be a mixture of cyclopropane esters, together with diethyl maleate and diethyl fumarate from dimerisation of the generated carbene. These biproducts were removed by extraction of an ethereal solution with aqueous $KMnO_4$, the main products being recovered by removal of the ether under vacuum. This was shown by P.M.R. to be a mixture of the cis (85b) and trans (85a) cyclopropanes (70% trans : 30% cis), by the deshielding of the alkyl protons when cis to the carboethoxy group.

Yield: 9.03 g (46%) b.p. 70^{o} at 0.2 torr

I.R. 3050 (m), 2950 (s), 1715 (s), 1170 (s)

P.M.R. 5.93 (q, 2H, J= 6.5 Hz, CH_2 of Et), 8.3-8.6 (c, 2H, H_α to carbonyl and H_β cis to carbonyl), 8.75 (t, 3H, J=6.5 Hz, CH_3 of Et), 8.87 (s, 3H, Me of major), 8.90 (s, 3H, Me of minor), 9.05 (s, 9H, tBu of minor), 9.10 (s, 9H, tBu of major), 9.1-9.7 (c, 1H, H_β trans to carbonyl)

(v) The mixture of cyclopropane esters (85), (16.33 g), was reduced with $LiAlH_4$ (2.5 g) in dry ether. After removal of the ether under reduced pressure, the product was obtained pure as a mixture of isomers and used as such.

Yield: 11.50 g (91%) b.p. 90^{o} at 16 torr

I.R. 3350 (m), 3050 (w), 2950 (s), 1030 (s)

P.M.R. 6.34 & 6.60 (c, 2H, J= 10.6 Hz, J= 6.6 Hz), 7.40 (s, 1H, broad - removed by D_2O), 8.96 (s, 3H, major), 9.00 (s, 3H, minor), 9.05 (s, 9H, minor), 9.16 (s, 9H, major), 9.25-10.15 (c, 3H)

(vi) The mixture of cyclopropane carbinols (86) (10.5 g) was oxidised with Jones Reagent according to the method of Organic Syntheses.[125] The product was purified by distillation under reduced pressure to give the cis and trans mixture.

Yield: 8.0 g (77%) b.p. $68-70^{o}$ at 10 torr

I.R. 2950 (s), 2720 (w), 1697 (s)

P.M.R. 0.52 (d, 1H, J= 4.0 Hz), 8.0-8.6 (c, 2H), 8.81 (s, 3H, major), 8.85 (s, 3H, minor), 8.88 (c, 1H), 9.01 (s, 9H, minor), 9.08 (s, 9H, major)

(vii) p-Toluene sulphonylhydrazine (10.6 g) was dissolved in a minimum amount of boiling A.R. methanol and the solution allowed to cool and solidify. The aldehyde (87), (8.0 g), was added, the mixture warmed until dissolved and then cooled in ice. The solvent was removed at room temperature on a rotary evaporator, the resulting oil being dissolved in ether and dried over anhydrous $CaCl_2$. After filtering the ether was removed under vacuum leaving a very thick yellow oil that would not crystallise.

Yield: 14.6 g (83%)

I.R. (CCl_4) 3180 (m), 2950 (s), 1623 (m), 1600 (m), 1160 (s)

(viii) Sodium hydride dispersion (2.0 g, 60% in oil), washed with dry ether to remove the oil, was covered with fresh dry ether in a flask fitted with a reflux condenser and a solution of the tosylhydrazone (88), (14.6 g), in dry ether was added in one portion. On warming, vigorous effervescence occurred and the solution was refluxed for some time. When cold the solution was filtered and the solvent removed on a rotary evaporator leaving a white solid that was dried in a vacuum dessicator.

Yield: 12.90 g (83%)

(ix) Decomposition of the Sodium salt (89)

The sodium salt (59), (12.9 g), was finely ground and mixed thoroughly with four times its bulk of sand. This mixture was introduced into a 1 litre Pyrex round-bottom flask with ground glass joint, to which was fitted a glass tap and joint that could be connected directly to a conventional vacuum line. The vessel was evacuated to 0.1 torr, sealed off at the tap and partially immersed in an oil bath, maintained at 140^{o}. After 24 hours the vessel was removed and the volatile

contents were distilled into a cold trap (liquid N_2) on the vacuum line.

Yield: 2.30 g (48% volatile product)

G.l.c. analysis (column A, 80°) of the product showed five major components which were separated by preparative g.l.c. (column F, 80°) and identified as the following by P.M.R. and I.R. analyses.

In order of elution:

2,3,3-trimethylbut-1-ene (84)

Yield: 14% of product

Identified by comparison with authentic sample.

3-t-butyl-3-methylcyclobutene (75)

Yield: 68% of product

For spectral data refer to page 37.

2-t-butylpenta-1,4-diene (90)

Yield: 12% of product

For spectral data refer to page 98.

2-t-butyl-2-methylmethylenecyclopropane (91)

Yield: 3% of product

I.R. 3080 (m), 2950 (s), 1790 (w), 1633 (s), 898 (s)

P.M.R. 5.39 (s, 1H), 5.51 (s, 1H), 8.58 (s, 3H), 8.88 (s, 9H), 9.10 (s, 1H, cyclopropyl), 9.21 (s, 1H, cyclopropyl)

(E)-4,5,5-trimethylhexa-1,3-diene (134)

Yield: 3% of product

For spectral data refer to page 98.

Preparation of 1,3-dienes

(I) Preparation of homoallylic alcohols

Allyl magnesium bromide (0.3 mole) was prepared according to the method of Organic Syntheses.[126] The ketone (0.2 mole) in dry ether was added slowly, with stirring, and after addition the mixture was refluxed for 1 hour. On cooling, the reaction mixture was poured onto ice/water in a large beaker, the precipitate dissolved with dil. sulphuric acid and the product extracted with ether and dried over $MgSO_4$. The solvent was removed under reduced pressure and the product was fractionally distilled.

(II) Dehydration of homoallylic alcohols

This was accomplished using a modification of the method of Lomas.[74]

To 0.0025 mole alcohol in 1 ml A.R. pyridine at 0° was added dropwise an excess (0.0035 mole) distilled thionyl chloride. The reaction mixture was stirred at 0° for 3 hours, during which time the colour changed from yellow through orange to red, and then extracted twice with ether. The extracts were washed thoroughly with water to remove pyridine and dried over K_2CO_3, after which the ether was removed under vacuum.

(NOTE: Products of these dehydrations should be stored in a freezer, since rapid polymerisation occurs at room temperature and with sunlight.)

In all cases g.l.c. analysis of the product showed several components which had to be separated by preparative g.l.c.

(a) (i) Preparation of 2,2,3-trimethylhex-5-en-3-ol (149)

Pinacolone (28.0 g) was reacted with allyl magnesium bromide in ether.

Yield: 34.2 g (86%) b.p. 61^{o} at 14 torr

I.R. 3480 (m), 3080 (w), 2950 (s), 1640 (m)

P.M.R. 4.10 (c, 1H), 4.90 (c, 1H, J_{gem}= 2.0 Hz, J_{cis}= 11.0 Hz), 4.98 (c, 1H, J_{gem}= 2.0 Hz, J_{trans}= 16.0 Hz), 7.80 (c, 2H), 8.10 (s, 1H, broad-removed by D_2O), 8.93 (s, 3H), 9.05 (s, 9H)

(ii) Dehydration

2,2,3-trimethylhex-5-en-3-ol (149), (28.9 g), was dehydrated with $SOCl_2$ (20.5 ml) and pyridine (79 ml).

Yield: 16.9 g (67%)

G.l.c. analysis (column A, 80^{o}) showed 2 components which were separated by preparative g.l.c. (column F, 64^{o}) and shown to be, in order of elution:

2-t-butylpenta-1,4-diene (90)

Yield: 36% of mixture

I.R. 3050 (m), 2950 (s), 1815 (m), 1630 (s), 1420 (s), 1390 (s), 900 (s)

P.M.R. 4.25 (c, 1H), 5.20 (c, 4H), 7.24 (d, 2H, J= 6.0 Hz), 8.94 (s, 9H)

(E)-4,5,5-trimethylhexa-1,3-diene (134)

Yield: 64% of mixture

I.R. 2950 (s), 1798 (w), 1643 (m), 1480 (s), 1380 (s), 910 (m)

P.M.R. (100 MHz) 3.54 (c, 1H, J_{trans}= 17.0 Hz, J_{cis} = $J_{2,3}$ = 10.5 Hz), 4.18 (d, 1H, broad, J= 10.5 Hz), 4.98 (c, 1H, J_{trans}= 17.0 Hz, J_{gem}= 2.5 Hz), 5.07 (c, 1H, J_{cis} = 10.5 Hz, J_{gem}= 2.5 Hz), 8.26 (s, 3H, broadened by allylic coupling J= 1.3 Hz), 8.92 (s, 9H)

C.M.R. Refer to page 54.

U.V. λ_{max} = 236.5 nm

(b) (i) Preparation of 2,3-dimethylhex-5-en-3-ol (146)

3-Methylbutan-2-one (25.0 g) was reacted with allyl magnesium bromide in ether.

Yield: 35.3 g (95%) b.p. 57° at 15 torr

I.R. 3380 (s), 3060 (m), 2940 (s), 1635 (m), 1370 (s), 990 (m), 910 (s)

P.M.R. 4.05 (c, 1H), 5.05 (c, 2H), 7.82 (d, 2H, broad, J= 6.5 Hz), 8.32 (septet, 1H, J= 7.0 Hz), 8.85 (s, 1H, removed by D_2O), 8.97 (s, 3H), 9.09 (2 × d, 6H, J= 7.0 Hz - methyl groups of isopropyl magnetically different due to adjacent chiral centre)

(ii) Dehydration

2,3-Dimethylhex-5-en-3-ol (146), (35.3 g), was dehydrated with $SOCl_2$ (28.2 ml) in pyridine (114 ml).

Yield: 14.4 g (50%)

G.l.c. analysis (column D, 120°) showed five components, separated by preparative g.l.c. (column G, 50°) and found to be in order of elution:

2-isopropylpenta-1,4-diene (151)

Yield: 21% of hydrocarbon

P.M.R. 4.25 (c, 1H), 5.00 (c, 2H), 5.28 (d, 2H, broad), 7.27 (d, 2H, broad, J= 6.5 Hz), 7.76 (septet, 1H, J= 6.5 Hz), 8.98 (d, 6H, J= 6.5 Hz)

4,5-dimethylhexa-1,4-diene (152)

Yield: 40% of hydrocarbon

P.M.R. 4.35 (c, 1H), 5.10 (d, 2H, broad), 7.30 (d, 2H, broad, J= 6.5 Hz), 8.36 (s, 9H, broad)

(Z)-4,5-dimethylhexa-1,3-diene (127)

Yield: 14% of hydrocarbon

I.R. 2950 (s), 1795 (w), 1650 (m), 1480 (m), 1390 (m), 1010 (m), 920 (s)

P.M.R. Refer to page 57.

C.M.R. Refer to page 54.

U.V. λ_{max} = 238 nm

(E)-4,5-dimethylhexa-1,3-diene (128)

Yield: 25% of hydrocarbon

I.R. Identical to Z isomer

P.M.R. Refer to page 57.

C.M.R. Refer to page 54.

U.V. λ_{max} = 238 nm

4-chloro-4,5-dimethylhex-1-ene (153)

I.R. 3060 (m), 1630 (m), 990 (m), 910 (s), 660 (m)

P.M.R. 4.20 (c, 1H), 4.90 (c, 2H), 7.50 (d, 2H, broad, J= 6.5 Hz), 8.09 (septet, 1H, J= 6.5 Hz), 8.56 (s, 3H), 8.96 (d, 6H, J= 6.5 Hz)

(c) (i) Preparation of 2-cyclopropylpent-4-en-2-ol (148)

Cyclopropyl methyl ketone (10.0 g) was reacted with allyl magnesium bromide in ether. The product was used without further purification for

the dehydration stage.

Yield: 14.4 g (96%)

I.R. 3420 (s), 3080 (m), 1643 (m), 990 (s), 920 (s)

P.M.R. 4.70 (c, 1H), 5.30 (c, 2H), 7.80 (s, 1H - removed by D_2O), 7.97 (d, 2H, J= 7.0 Hz), 9.15 (s, 3H), 9.20-10.0 (c, 5H).

(ii) Dehydration

2-Cyclopropylpent-4-en-2-ol (148), (14.4 g), was dehydrated with $SOCl_2$ (11.5 ml) in pyridine (46 ml).

Yield: 3.56 g (29%)

G.l.c. analysis (column C, 140°) of the product showed three components which were separated by preparative g.l.c. (column F, 120°) and found to be in order of elution:

2-cyclopropylpenta-1,4-diene (158)

Yield: 25% of hydrocarbon

P.M.R. 4.75 (c, 1H), 5.0 (c, 2H), 5.40 (s, 2H, broad), 7.28 (d, 2H, J= 6.0 Hz), 8.80 (c, 1H), 9.3-9.7 (c, 4H)

Mixture of (E)- and (Z)-4-cyclopropylpenta-1,3-dienes

Yield: 75% of hydrocarbon

I.R. 3080 (m), 2980 (s), 1790 (w), 1630 (m), 1410 (m), 1370 (m), 885 (m)

4-chloro-4-cyclopropylpent-1-ene (159)

I.R. 3080 (m), 2970 (s), 1640 (m), 1440 (s), 990 (m), 920 (s), 660 (m)

P.M.R. (Standardised against $CHCl_3$ at 2.77 τ) 4.40 (c, 1H), 5.10 (c, 2H), 6.70 (c, 2H), 7.50 (c, 4H), 8.45 (c, 4H including s, 3H)

M.S. m^+ = 146,144 (1 Cl atom)

The mixture of (E)- and (Z)-1,3-dienes, although seen as one peak when using PPG column phase, was resolved into its two components using PPGA (column D, 65°) and could be separated on a preparative scale using column G at 60°. The compounds were shown to be in order of elution:

(E)-4-cyclopropylpenta-1,3-diene (132)

Yield: 37% of hydrocarbon

P.M.R. Refer to page 57.

C.M.R. Refer to page 54.

U.V. λ_{max} = 241 nm

(Z)-4-cyclopropylpenta-1,3-diene (131)

Yield: 38% of hydrocarbon

P.M.R. and C.M.R. as for (E) isomer

U.V. λ_{max} = 241 nm

(d) (i) Preparation of 4-methylhept-6-en-4-ol (147)

Pentan-2-one (6.5 g) was reacted with allyl magnesium bromide in ether.

Yield: 9.05 g (94%)

I.R. 3380 (s), 3060 (w), 2950 (s), 1640 (m), 1375 (m), 910 (m)

P.M.R. 4.11 (c, 1H, $J_{5,6}$= 7.0 Hz, J_{cis}= 9.0 Hz, J_{trans}= 18.0 Hz), 4.91 (c, 1H, J_{cis}= 9.0 Hz, J_{gem}= 2.6 Hz), 5.01 (c, 1H, J_{trans}= 18.0 Hz, J_{gem}= 2.6 Hz), 6.36 (s, 1H - removed by D_2O), 7.82 (d, 2H, J= 7.0 Hz), 8.50-9.2 (c, 10H including 8.89 (s, 3H))

(ii) Dehydration

4-Methylhept-6-en-4-ol (147), (9.05 g), was dehydrated with $SOCl_2$ (7.4 ml) in pyridine (20 ml).

Yield: 4.11 g (52%)

G.l.c. analysis (column B, 68°) of the product showed six components, which were separated preparatively using column G at 40°. Of the first component, amounting to 5% of the hydrocarbon product, insufficient was collected to obtain a positive identification. The second and third products (in order of elution) were collected together and tentatively identified as:

(Z)- and (E)-4-methylhepta-1,4-dienes (156 and 155 respectively) by order of elution from the g.l.c. and the P.M.R. spectrum

Yield: 40% of hydrocarbon

P.M.R. 4.1-4.5 (c, 1H), 4.8-5.3 (c, 3H), 7.30 (d, 2H, J= 6.0 Hz), 7.97 (c, 2H), 8.35 (d, 3H of one isomer, J= 1.3 Hz), 8.42 (s, 3H of other isomer), 9.05 (t, 3H, broad, J= 7.0 Hz)

The three remaining components were positively identified as:

(Z)-4-methylhepta-1,3-diene (129)

Yield: 22% of hydrocarbon

P.M.R. See page 57.

C.M.R. See page 54.

(E)-4-methylhepta-1,3-diene (130)

Yield: 33% of hydrocarbon

P.M.R. and C.M.R. as for (Z) isomer

4-chloro-4-methylhept-1-ene (159)

P.M.R. 4.50 (c, 1H), 4.80-5.20 (c, 2H), 7.50 (d, 2H, J= 7.0 Hz), 8.30-9.20 (c, 10H including 8.51 (s, 3H))

(e) (i) Preparation of 2-phenylpent-4-en-2-ol (150)

Acetophenone (7.0 g) was reacted with allyl magnesium bromide in ether.

Yield: 8.6 g (92%)

I.R. 3430 (m), 3070 (w), 3030 (w), 2980 (m), 1642 (m), 1605 (w), 1448 (m), 999 (m), 915 (m), 790 (s)

P.M.R. 2.60 (c, 5H), 4.35 (c, 1H), 4.80-5.20 (c, 2H), 7.40 (s, 1H - removed by D_2O), 7.49 (d, 2H, J= 7.0 Hz), 8.55 (s, 3H)

(ii) Dehydration

2-Phenylpent-4-en-2-ol (150), (8.6 g), was reacted with $SOCl_2$ (5.5 ml) in pyridine (20 ml).

Yield: 3.6 g (38%)

Analysis of the product by I.R., N.M.R. and M.S. showed it to be a single compound:

4-chloro-4-phenylpent-1-ene (160)

I.R. 3060 (w), 2970 (m), 1640 (w), 1490 (m), 1440 (m), 1380 (m), 920 (m), 700 (s)

P.M.R. 2.70 (c, 5H), 4.35 (c, 1H), 4.80-5.20 (c, 2H), 7.17 (d, 2H, J= 7.0 Hz), 8.12 (s, 3H)

M.S. m^+ = 182,180,144 (1 Cl atom, with loss of HCl)

However g.l.c. analysis (column A, 110°) showed three components, the percentages of which varied with column temperature. It was postulated

that the three components corresponded to the chloro compound and its dehydrochlorination products. To obtain samples of these products the preparative g.l.c. was run at a high column temperature (column F, 160°) with an even higher injection port temperature (190°). This system gave two components, shown on the trace, which were collected at -78° and identified as:

2-phenylpenta-1,4-diene (161)

Yield: 45%

I.R. 3080 (m), 3060 (m), 2980 (m), 1620 (m), 1440 (s), 915 (s), 895 (s), 690 (s)

P.M.R. 2.74 (c, 5H), 4.05 (c, 1H), 4.60-5.10 (c, 4H), 6.79 (d, 2H, J= 7.0 Hz)

(E)-4-phenylpenta-1,3-diene (138)

Yield: 43%

I.R. 3080 (m), 3060 (m), 1670 (s), 1620 (m), 900 (s), 690 (s)

P.M.R. 2.63 (c, 5H), 3.25 (2 × d, 1H, J= 10.0 Hz, J= 17.0 Hz), 3.46 (s, 1H, broad), 4.50-4.90 (c, 2H), 7.77 (s, 3H, broad)

Further g.l.c. analysis (column A, 100°) of the first fraction showed the presence of another component, overlapping on the g.l.c. trace with 2-phenylpenta-1,4-diene, and amounting to 12% of the mixture. This component was tentatively identified as (Z)-4-phenylpenta-1,3-diene (137), from a singlet in the N.M.R. spectrum of the first fraction at 7.91 τ which could not be otherwise assigned. This signal corresponded closely to the expected position of the methyl group in the (Z)-diene. This assignment was later confirmed by g.l.c. comparison with an authentic

sample of the (Z)-diene obtained from the pyrolysis of 3-methyl-3-phenyl cyclobut-1-ene.

(f) Preparation of (Z)-4,5,5-trimethylhexa-1,3-diene (133)

This was accomplished by the photo-sensitized isomerisation of the (E)-isomer. (E)-4,5,5-trimethylhexa-1,3-diene (134), (0.94 g), and acetophenone (0.91 g) in distilled n-pentane (200 ml) were irradiated with a medium-pressure Hg lamp for 1 hour, after which time g.l.c. analysis (column D, 120°) showed 41% of the (Z)-isomer present.

The solvent was removed under reduced pressure and the product purified by column chromatography on silica, the dienes being eluted with 30-40° petrol. Separation of the two isomers, (133) and (134), could not be achieved using any of the preparative columns available, so that all spectral data of the (Z)-isomer was accumulated from the (Z)/(E) mixture.

P.M.R. Refer to page 57.

C.M.R. Refer to page 54.

U.V. λ_{max} = 237 nm, with shoulder at lower wavelength

Preparation of Cyclopropyldiphenylsulphonium Fluoroborate (97)

Silver tetrafluoroborate (100) was prepared from silver fluoride (36.0 g) and boron trifluoride gas in nitromethane (40 ml), according to the method of Olah and Quinn.[127] The product was a light-grey solid, which was stored in a dark container within a dessicator.

Yield: 51.0 g (99%)

1-Chloro-3-iodopropane (99) was prepared either from 3-chloropropan-1-ol and iodine in the presence of red phosphorus, as given by Vogel,[123]

or from 1-bromo-3-chloropropane by treatment with sodium iodide in acetone, according to the method of Trost.[65] The latter method proved to be the more straightforward and afforded the higher yields. The product was a colourless liquid, turning yellow on storage.

b.p. 60^{o} at 10 torr (lit: $47-59^{o}$ at 6 torr[65])

I.R. 2950 (m), 1438 (m), 1210 (s), 760 (m), 660 (m)

P.M.R. 6.38 (t, 2H, J= 6.0 Hz), 6.70 (t, 2H, J= 6.0 Hz), 7.77 (c, 2H)

3-Chloropropyldiphenylsulphonium fluoroborate (101) was prepared from diphenyl sulphide (98), 99.0 g), 1-chloro-3-iodopropane (99), 360 g) and silver tetrafluoroborate (100), (80.0 g), in nitromethane, according to the method of Trost.[65] The crystalline product was washed thoroughly with dry ether and dried under vacuum.

Yield: 127.0 g (70%) m.p. $102-104^{o}$ (lit: 108^{o} [65])

P.M.R. ($CDCl_3$) 2.20 (c, 10H), 5.73 (t, 2H, J= 8.0 Hz), 6.26 (t, 2H, J= 6.5 Hz), 7.78 (c, 2H)

The fluoroborate (101), (127.0 g), was reacted with sodium hydride (16.7 g, 60% dispersion in oil) in purified T.H.F. to give the cyclopropyldiphenylsulphonium fluoroborate (97). The product was recrystallised from methanol and dried under vacuum.

Yield: 88.0 g (78%) m.p. $138-139^{o}$ (lit: 139^{o} [65])

I.R. 3040 (m), 1582 (m), 1050 (s)

P.M.R. ($CDCl_3$) 2.20 (c, 10H), 6.31 (c, 1H), 8.30-8.70 (c, 4H)

The Reaction of Cyclopropyldiphenylsulphonium fluoroborate, C.D.S.F., (97) with Ketones

In all experiments the apparatus used consisted of a 100 ml 3-neck flask, fitted with a dry N_2 inlet, condenser and $CaCl_2$ drying tube, so that a dry N_2 atmosphere could be maintained throughout the reaction. The apparatus was initially flamed for a few minutes whilst a steady stream of nitrogen passed through it. Dimethyl sulphoxide (DMSO, ex Koch Light), the solvent, was purified by shaking thoroughly with $CaSO_4$, filtering and distilling at 10 torr, being stored over activated 4A molecular sieves prior to use.

Cyclopropyldiphenylsulphonium fluoroborate (97), (3.14 g, 10 millimole) and the ketone (10 millimole) were dissolved in DMSO (30 ml) in the apparatus, and stirred magnetically. Freshly powdered KOH (1.12 g, 20 millimole) was added in one portion and the mixture was stirred rapidly for a suitable period, determined by I.R. monitoring of the reaction mixture. The initial solutions turned orange/brown on the addition of the KOH. Work-up of the reaction mixture was effected by one of the following procedures, to give the intermediate oxaspiropentane by the first method and the cyclobutanone directly by the second.

Method A: The reaction mixture was quenched with cold water, and extracted twice with 30-40^{o} petrol. The extracts were dried over $MgSO_4$, filtered and the solvent removed on a water-bath, using a Perkin Head fitted to a fractionating column. The product was distilled under reduced pressure, to yield the oxaspiropentane. This was converted to the cyclobutanone by heating in a closed vessel under vacuum for several hours.

Method B: The reaction mixture was poured onto a cold, aqueous 1 M

fluoroboric acid solution (30 ml) and extracted twice with ether. The extracts were washed with water to remove traces of DMSO, dried over $MgSO_4$ and distilled to remove the solvent. The product, a mixture of the cyclobutanone and diphenyl sulphide, was then purified either by distillation under reduced pressure or by column chromatography on silica, the eluant being 30-40° petrol. (R_F values: for Ph_2S = 0.7, cyclobutanones = 0.1)

(i) Reaction with pinacolone

C.D.S.F. (97), (5.03 g, 16 millimole) and pinacolone (112), (1.60 g, 16 millimole), were treated with KOH (1.80 g, 32 millimole) in DMSO for 24 hours. The product, 2-t-butyl-2-methyloxaspiropentane, was obtained using Method A.

Yield: 1.27 g (57%) b.p. 60° at 25 torr

I.R. 3060 (w), 1070 (m), 1020 (m), 830 (m)

P.M.R. 8.67 (s, 3H), 8.90 (c, 2H), 9.04 (s, 9H), 9.30-9.50 (c, 2H)

Heating under vacuum at 100° for 3 hours yielded 2-t-butyl-2-methylcyclobutan-1-one (113).

I.R. 2950 (s), 1775 (s), 1470 (m), 1365 (m), 1050 (m)

P.M.R. 6.40-7.00 (c, 2H, αCH_2), 7.90-8.60 (c, 2H, βCH_2), 8.88 (s, 3H), 9.09 (s, 9H)

(ii) Reaction with 3-methylbutan-2-one

C.D.S.F. (97), (11.4 g, 36 millimole), and 3-methylbutan-2-one (106), (3.1 g, 36 millimole), were treated with KOH (4.0 g, 72 millimole) in DMSO for 22 hours. 2-Methyl-2-i-propyloxaspiropentane was isolated using Method A.

Yield: 2.0 g (44%) b.p. 40^{o} at 25 torr

I.R. 3070 (w), 1180 (m), 1060 (w), 995 (m)

P.M.R. 8.25 (septet, 1H, J= 6.5 Hz), 8.72 (s, 3H), 8.90- (c, 10H including (d, 6H, J= 6.5 Hz))

Heating at 130^{o} for 12 hours gave 2-methyl-2-i-propylcyclobutan-1-one (107).

I.R. 2950 (s), 1770 (s), 1450 (m), 1050 (m), 1030 (m)

P.M.R. 7.25 (c, 2H, αCH_2), 7.80-8.70 (c, 3H, βCH_2 + isopropyl CH), 8.91 (s, 3H), 9.08 (d, 6H, J= 6.5 Hz)

(iii) Reaction with cyclopropylmethyl ketone

C.D.S.F. (97), (12.6 g, 40 millimole), and cyclopropylmethyl ketone (110), (3.36 g, 40 millimole), were treated with KOH (4.5 g, 80 millimole) in DMSO for 15 hours. Extraction using Method A gave 2-cyclopropyl-2-methylcyclobutan-1-one (111) directly.

Yield: 3.0 g (60%) b.p. 40^{o} at 25 torr

I.R. 3070 (w), 1777 (s), 1050 (m), 1017 (m)

P.M.R. 7.15 (c, 2H, αCH_2), 8.20 (c, 2H, βCH_2), 8.78 (s, 3H), 9.0-10.0 (c, 5H)

(iv) Reaction with pentan-2-one

C.D.S.F. (97), (5.67 g, 18 millimole), and pentan-2-one (108), (1.55 g, 18 millimole) were treated with KOH (2.0 g, 36 millimole) in DMSO for 12 hours. Extraction using Method B gave a mixture of Ph_2S and 2-methyl-2-propylcyclobutan-1-one (109), separated by the distillation of the cyclobutanone at 0.05 torr into a -78^{o} trap.

Yield: 1.87 g (83%)

I.R. 2960 (s), 2880 (m), 1780 (s), 1455 (m), 1390 (w), 1070 (m)

P.M.R. 7.07 (c, 2H, αCH_2), 8.15 (c, 2H, βCH_2), 8.30-9.20 (c, 10H, including 8.85 (s, 3H))

(v) Reaction with acetophenone

C.D.S.F. (97), (3.14 g, 10 millimole) and acetophenone (116), (1.20 g, 10 millimole), were treated with KOH (1.12 g, 20 millimole) in DMSO for 4 hours. The product, 2-methyl-2-phenylcyclobutan-1-one (117), was extracted using Method B and purified by distillation under reduced pressure.

Yield: 1.40 g (85%) b.p. 73^{o} at 0.4 torr

I.R. 3075 (w), 2960 (s), 1781 (s), 1600 (w), 1495 (m), 1445 (m), 1055 (m), 1028 (m), 765 (m), 705 (s)

P.M.R. 2.70 (s, 5H, broad), 7.00 (c, 2H), 7.80 (c, 2H), 8.51 (s, 3H)

M.S. $m^{+} = 160$

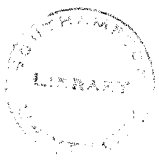
(vi) Reaction with p-methoxyacetophenone

C.D.S.F. (97), (3.14 g, 10 millimole), and p-methoxyacetophenone (118), (1.50 g, 10 millimole), were treated with KOH (1.12 g, 20 millimole) in DMSO for 5 hours. The product, 2-(4'-methoxyphenyl)-2-methylcyclobutan-1-one (119), was extracted using Method B and used without further purification.

Yield: 3.47 g of mixture with Ph_2S (93%)

I.R. 3050 (m), 2950 (m), 1770 (s), 1600 (m), 1510 (s), 1250 (s), 1180 (m), 830 (m)

P.M.R. 3.00 (Abq, 4H, J= 9.0 Hz), 6.30 (s, 3H), 6.80 (c, 2H), 7.80 (c, 2H), 8.55 (s, 3H)



(vii) Reaction with m-methoxyacetophenone

C.D.S.F. (97), (1.57 g, 5 millimole), and m-methoxyacetophenone (120), (0.75 g, 5 millimole), were treated with KOH (0.56 g, 10 millimole) in DMSO for 4 hours. The products, 2-(3'-methoxyphenyl)-2-methylcyclobutan-1-one (121) and Ph_2S (98), were extracted by Method B and used without further purification.

Yield: 1.80 g of mixture (96%)

I.R. 3050 (w), 2970 (m), 1770 (s), 1600 (m), 1290 (m), 780 (m)

P.M.R. 2.80-3.40 (c, 4H), 6.35 (s, 3H), 7.10 (c, 2H), 7.75 (c, 2H), 8.59 (s, 3H)

(viii) Reaction with p-acetylbenzonitrile

C.D.S.F. (97), (1.57 g, 5 millimole), and p-acetylbenzonitrile (122), (0.725 g, 5 millimole), were treated with KOH (0.56 g, 10 millimole) in DMSO for 3 hours. The products, 2-(4'-cyanophenyl)-2-methylcyclobutan-1-one (123) and Ph_2S (98), were extracted using Method B and used without further purification.

Yield: 1.61 g (87%)

I.R. 3060 (w), 2960 (w), 2230 (m), 1775 (s), 1608 (w), 1503 (m), 1060 (m), 840 (m)

P.M.R. 2.70 (c, 4H), 6.90 (c, 2H), 7.80 (c, 2H), 8.47 (s, 3H)

(ix) Reaction with 3,3,4,4,4-pentadeuterobutan-2-one

C.D.S.F. (97), (2.24 g, 7 millimole), and 3,3,4,4,4-pentadeuterobutan-2-one (114), (0.55 g, 7 millimole), were treated with KOH (0.80 g, 14 millimole) in DMSO for 3 hours. The product, 2-methyl-2-pentadeutero ethylcyclobutan-1-one (115), was extracted using Method B and purified by distillation into a -78^{o} trap.

Yield: 0.54 g (65%)

I.R. 3530 (w), 2950 (s), 2230 (m), 2100 (w), 1770 (s), 1450 (m), 1120 (m), 1050 (s)

P.M.R. 7.08 (c, 2H, CH), 7.95 (c, 2H, CH), 8.84 (s, 3H)

M.S. m/e = 117, 89

Preparation of Tosylhydrazones

Equimolar quantities of p-toluenesulphonylhydrazine and the cyclobutanone were mixed in a small quantity of A.R. methanol and the mixture heated until all had dissolved. 1 drop of conc. HCl was added and the solution cooled in a freezer overnight. The crystalline tosylhydrazone was filtered off and the filtrate was quenched with water to obtain more product. Both crops were combined, recrystallised from methanol and dried thoroughly under vacuum.

(i) 2-t-butyl-2-methylcyclobutan-1-one tosylhydrazone (126)

From the cyclobutanone (113), (1.10 g), and p-tosylhydrazine (1.50 g).

Yield: 0.96 g (40%) m.p. 159-161°

I.R. 3200 (m), 1592 (w), 1165 (m)

P.M.R. ($CDCl_3$) 2.0-2.8 (c, 5H, aromatic & N-H), 7.5-8.1 (c, 7H, 2 × cyclobutane CH_2, including 7.63 (s, 3H, aromatic Me) 8.90 (s, 3H), 9.08 (s, 9H)

M.S. m/e = 308, 252

(ii) 2-methyl-2-i-propylcyclobutan-1-one tosylhydrazone

From the cyclobutanone (107), (2.0 g), and p-tosylhydrazine (2.8 g).

Yield: 2.0 g (43%) m.p. 133-135°

I.R. 3200 (m), 1595 (w), 1165 (m)

P.M.R. ($CDCl_3$) 2.0-2.8 (c, 5H, aromatic & N-H), 7.4-8.7 (c, 8H, 2 × cyclobutane CH_2 & i-propyl C-H, including 7.64 (s, 3H)), 8.93 (s, 3H), 9.07 (d, 6H, J= 6.5 Hz)

(iii) 2-cyclopropyl-2-methylcyclobutan-1-one tosylhydrazone

From the cyclobutanone (111), (3.0 g), and p-tosylhydrazine (4.5 g).

Yield: 2.26 g (32%) m.p. 128-129°

I.R. 3200 (m), 3080 (w), 1675 (w), 1595 (m), 1165 (s)

P.M.R. ($CDCI_3$) 2.1-2.8 (c, 5H, aromatic & N-H), 7.50 (c, 2H, αCH_2), 7.62 (s, 3H), 8.30 (c, 2H, βCH_2), 8.84 (s, 3H), 9.0-10.0 (c, 5H)

M.S. $m^+ = 292$

(iv) 2-methyl-2-propylcyclobutan-1-one tosylhydrazone

From the cyclobutanone (109), (1.87 g), and p-tosylhydrazine (2.76 g).

Yield: 3.60 g (83%) m.p. 135-136°

I.R. 3200 (m), 1680 (w), 1598 (w), 1410 (m), 1348 (s), 1175 (s)

P.M.R. ($CDCI_3$) 2.0-2.8 (c, 5H, aromatic & N-H), 7.1-7.7 (c, 5H, αCH_2 and including 7.58 (s, 3H)), 8.0-8.9 (c, 9H, including 8.88 (s, 3H)), 9.0-9.3 (c, 3H, Me of propyl)

M.S. $m^+ = 294$

(v) 2-methyl-2-phenylcyclobutan-1-one tosylhydrazone

From the cyclobutanone (117), (1.40 g), and p-tosylhydrazine (1.58 g).

Yield: 2.43 g (87%) m.p. 161-162°

I.R. 3200 (s), 1690 (w), 1595 (w), 1410 (m), 1335 (s), 1170 (s)

P.M.R. ($CDCI_3$) 2.0-2.8 (c, 10H, aromatic & N-H), 7.25 (c, 2H, αCH_2), 7.59 (s, 3H), 7.80 (c, 2H, βCH_2), 8.54 (s, 3H)

M.S. $m^+ = 328$

(vi) 2-(4'-methoxyphenyl)-2-methylcyclobutan-1-one tosylhydrazone

From a mixture of the cyclobutanone (119) and Ph_2S (3.40 g) and p-tosylhydrazine (1.71 g).

Yield: 2.70 g (84%) m.p. 165-167°

I.R. 3200 (m), 1690 (w), 1590 (w), 1505 (m), 1330 (m), 1180 & 1170 (s), 1035 (m)

P.M.R. ($CDCl_3$) 2.0-3.5 (c, 9H, aromatic & N-H), 6.22 (s, 3H, $-OCH_3$), 7.0-8.2 (c, 7H, 2 × CH_2 and including 7.55 (s, 3H)), 8.55 (s, 3H)

M.S. m^+ = 358

(vii) 2-(3'-methoxyphenyl)-2-methylcyclobutan-1-one tosylhydrazone

Prepared directly from a mixture of the cyclobutanone (121) and Ph_2S (1.79 g) and p-tosylhydrazine (0.89 g).

Yield: 1.10 g (65%) m.p. 138-140°

I.R. 3200 (m), 1690 (w), 1595 (w), 1170 (s)

P.M.R. ($CDCl_3$) 2.0-3.4 (c, 9H, aromatic & N-H), 6.28 (s, 3H, $-OCH_3$), 7.20 (c, 2H, αCH_2), 7.60 (s, 3H), 7.80 (c, 2H, CH), 8.52 (s, 3H)

M.S. m^+ = 358

(viii) 2-(4'-cyanophenyl)-2-methylcyclobutan-1-one tosylhydrazone

From a mixture of the cyclobutanone (123) and Ph_2S (1.61 g) and p-tosylhydrazine (0.70 g).

Yield: 0.54 g (38%) m.p. 186-187°

I.R. 3200 (m), 2220 (s), 1590 (w), 1335 (s), 1165 (s)

P.M.R. ($CDCl_3$) 2.0-2.8 (c, 9H, aromatic & N-H), 7.0-8.0 (c, 7H, including 7.53 (s, 3H), 8.51 (s, 3H)

M.S. m^+ = 353

(ix) 2-methyl-2-pentadeuteroethylcyclobutan-1-one tosylhydrazone

From the cyclobutanone (115), (0.54 g), and p-tosylhydrazine (0.86 g).

Yield: 1.04 g (79%) m.p. 125-126°

I.R. 3200 (m), 2220 (w), 1670 (w), 1595 (m), 1330 (s), 1170 (s), 815 (m)

P.M.R. ($CDCl_3$) 2.0-2.8 (c, 5H, aromatic ABq & N-H), 7.2-7.6 (c, 5H, αCH_2, including 7.58 (s, 3H)), 8.30 (c, 2H, βCH_2), 8.88 (s, 3H)

M.S. m/e = 285, 130

Preparation of Cyclobutenes from tosylhydrazones and methyl lithium

A solution of methyl lithium in dry diethyl ether was prepared from lithium wire and methyl iodide. The molarity of the solution was determined by running an aliquot of the solution into excess water and titration of this solution against standard acid using phenol phthalein as indicator.

A suspension of the tosylhydrazone in dry ether was prepared, under dry N_2, in a 3-neck flask fitted with a pressure-equalised dropping funnel, magnetic stirrer, condenser and dry N_2 inlet. The suspension was stirred vigorously at room temperature and a greater-than-twice molar amount of the methyl lithium solution was added slowly from the dropping funnel. After a small portion had been added, vigorous effervescence occurred and the suspension dissolved giving a colourless solution. Further addition of methyl lithium gradually liberated a white precipitate, which turned yellow after all the solution had been added. The reaction mixture was stirred, under N_2, overnight, and then quenched

with excess water. The yellow ethereal layer was separated, the aqueous layer extracted with ether, and the extracts dried over $MgSO_4$. After filtering, the solvent was removed carefully using a fractionating column and Perkin Head at atmospheric pressure, leaving the cyclobutene slightly contaminated with a solid.

The alkyl cyclobutenes were purified by trap-to-trap distillation on the vacuum line, whereas the aromatic compounds were purified by extraction of the residues with n-pentane and removal of the solvent under vacuum.

G.l.c. and N.M.R. analyses of the products showed them to be pure compounds. In general, yields of these reactions were not established, though one trial reaction gave an isolated yield of 71%.

(i) 3-t-butyl-3-methylcyclobut-1-ene (75)

I.R. 3140 (m), 3040 (s), 1640 (s), 1470 (s)

P.M.R. Refer to page 37.

M.S. $m^+ = 124$

Verified by g.l.c. comparison with authentic sample, prepared as described earlier.

(ii) 3-methyl-3-i-propylcyclobut-1-ene (72)

I.R. 3120 (m), 1615 (m), 1440 (s), 920 (m)

P.M.R. Refer to page 37.

M.S. $m^+ = 110$

(iii) 3-cyclopropyl-3-methylcyclobut-1-ene (74)

I.R. 3120 (w), 3080 (m), 1645 (m), 1460 (s), 1300 (m)

P.M.R. Refer to page 37.

M.S. $m^+ = 108$

(iv) 3-methyl-3-propylcyclobut-1-ene (73)

I.R. 3120 (w), 1640 (m), 1450 (s)

P.M.R. Refer to page 37.

M.S. $m^+ = 110$

(v) 3-methyl-3-phenylcyclobut-1-ene (77)

I.R. 3100 (w), 3040 (m), 1680 (w), 1450 (s)

P.M.R. Refer to page 37.

(vi) 3-(4'-methoxyphenyl)-3-methylcyclobut-1-ene (78)

I.R. 3120 (w), 3040 (m), 1680 (w), 1610 (m), 1450 (s), 1300 (s), 1030 (m)

P.M.R. Refer to page 37.

(vii) 3-(3'-methoxyphenyl)-3-methylcyclobut-1-ene (79)

I.R. 3110 (w), 3040 (m), 1685 (w), 1600 (m), 1450 (s), 1280 (m)

P.M.R. Refer to page 37.

(viii) 3-(4'-cyanophenyl)-3-methylcyclobut-1-ene (80)

I.R. 3130 (w), 3050 (m), 2230 (m), 1685 (m), 1600 (w), 1450 (s), 1260 (s)

P.M.R. Refer to page 37.

(ix) 3-methyl-3-pentadeuteroethylcyclobut-1-ene (76)

I.R. 3120 (w), 2220 (w), 1640 (m), 1450 (m)

P.M.R. Refer to page 37.

M.S. m/e = 101, 86

The Pyrolysis of the Cyclobutenes

Pyrolyses were carried out in an "aged" glass vessel fitted with a Teflon Rotaflow valve and a B10 joint for connection to the vacuum line. A small quantity of sample was introduced into the vessel, using a 100 µl syringe; the vessel was then frozen down with liquid N_2 and evacuated to 0.1 torr. After closing the valve, the contents were allowed to warm to room temperature to degas before being refrozen and evacuated again.

The vessel was removed from the vacuum line and immersed in an oil bath maintained at a suitable temperature for a given length of time (generally 180° for 1 hour). Following this the vessel was cooled quickly and the contents taken up in distilled n-pentane prior to g.l.c. analysis. Several g.l.c. columns and conditions were tried for each sample to ensure that maximum resolution was obtained, between the Z and E-isomers for the alkyl compounds, and between the Z-diene and the cyclobutene in the aryl series. Pyrolyses were repeated to ensure reproducibility.

N.B. Preliminary investigations were always performed to ensure that the starting materials and products were stable under the g.l.c. conditions employed.

Kinetic Runs

For the kinetic analyses the following modifications to the above method were used:

(a) A large thermostatted oil-bath ($\pm 0.05^{\circ}$) was used, that was allowed to equilibrate for at least 12 hours before use.

(b) The time of the pyrolysis was recorded using a calibrated stop-clock.

(c) Samples were frozen in a - 78° bath after pyrolysis, to ensure rapid quenching of the reaction.

A plot of $\log_{10}$(amount starting material remaining) against time (seconds) gave a straight line at each temperature, giving a value of the rate constant, k, at that temperature. A plot of $\log_e k$ against $1/T^{\circ}K$ gave a straight line for each sample studied, from which the rate equations were obtained.

(i) 3-t-butyl-3-methylcyclobutene (75)

Pyrolyses at 180° for 1.0 hour gave 68% E and 32% Z-4,5,5-trimethylhexa-1,3-diene. Separated using column D at 120°.

(ii) 3-methyl-3-i.propylcyclobutene (72)

Pyrolyses at 180° for 1.0 hour gave 65.5% Z and 34.5% E-4,5-dimethylhexa-1,3-diene. Separated using column D at 90°.

(iii) 3-cyclopropyl-3-methylcyclobutene (74)

Pyrolyses at 180° for 2.0 hours gave 57% E and 43% Z-4-cyclopropylpenta-1,3-diene. Separated using column D at 65°.

(iv) 3-methyl-3-propylcyclobutene (73)

Pyrolyses at 180° for 1.0 hour gave 62% Z and 38% E-4-methylhepta-1,3-diene. Separated using column B at 50°.

(v) 3-methyl-3-phenylcyclobutene (77)

Pyrolyses at 180° for 15.0 minutes gave 30% Z and 70% E-4-phenylpenta-1,3-diene. Repetition at 161° for 1.0 hour gave the same result. Separated using column E at 100°.

(vi) 3-(4'-methoxyphenyl)-3-methylcyclobutene (78)

Pyrolyses at 180° for 20.0 minutes gave 52% Z and 48% E-4-(4'-methoxyphenyl)penta-1,3-diene. Separated using column E at 110°.

(vii) 3-(3'-methoxyphenyl)-3-methylcyclobutene (79)

Pyrolyses at 161° for 15.0 minutes gave 32% Z and 68% E-4-(3'-methoxyphenyl)penta-1,3-diene. Separated using column E at 110°.

(viii) 3-(4'-cyanophenyl)-3-methylcyclobutene (80)

Pyrolyses at 161° for 11.0 minutes gave 45% Z and 55% E-4-(4'-cyanophenyl)penta-1,3-diene. Separated using a 3% Carbowax 20M column (1.5 metre) at 100°.

(ix) 3-methyl-3-pentadeuteroethylcyclobutene (76)

Pyrolyses at 180° for 1.0 hour gave 61% Z and 39% E-4-methyl-5,5,6,6,6-pentadeuterohexa-1,3-diene. Separated using column D at 60°.

Identification of pyrolysis products by 1,5 H shift

(i) t-Butyl dienes

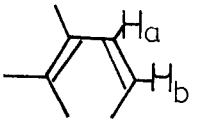
A sample of the conjugated diene obtained from the dehydration of the alcohol (149), known to be a single isomer by g.l.c., was pyrolysed in a sealed glass vessel under vacuum at 240° for 1 hour. G.l.c. analysis (column A, 80°) showed 2 components in the product: the original diene and another of much shorter retention time. Separation by preparative g.l.c. (column F, 80°) enabled the unknown to be identified as:

(Z)-2-t-butylpenta-1,3-diene (162)

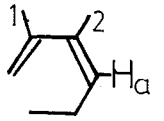
P.M.R. 4.20 (c, 2H), 5.18 (s, 1H, broad), 5.38 (s, 1H, broad), 8.28 (d, 3H, J= 5.5 Hz), 8.94 (s, 9H)

(ii) iso-Propyl dienes

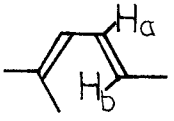
A sample (70 mg) of the conjugated diene of shorter retention time, obtained from the dehydration of the alcohol (146), was pyrolysed at 240° for 2.0 hours. G.l.c. analysis (column D, 120°) showed several components, which were separated by preparative g.l.c. (column G, 50°) and found to be:

(Z)-2,3-dimethylhexa-2,4-diene (163) 

P.M.R. 4.20 (d, $1H_a$, broad, J_{cis}= 12.0 Hz), 4.67 (2 × q, $1H_b$, J_{cis}= 12.0 Hz, J_{HCH_3}= 7.0 Hz), 8.34 (s, 6H, broad), 8.43 (s, 3H), 8.49 (2 × d, 3H, J_{HCH_3}= 7.0 Hz, J_{allyl}= 1.5 Hz)

(Z)-2,3-dimethylhexa-1,3-diene (164) 

P.M.R. 4.49 (broad t, H_a, J= 7.0 Hz), 5.11 (d, 1H, J= 2.0 Hz), 5.22 (broad s, 1H), 7.95 (c, 2H, CH_2 of Et), 8.13 (s, 3H, Me $_1$), 8.24 (s, 3H, Me $_2$ - irradiation at 8.24 decouples H_a of allylic coupling), 8.99 (t, 3H, J= 7.0 Hz, Me of Et)

(E)-2,3-dimethylhexa-2,4-diene (165) 

P.M.R. 3.62 (d, H_a, J_{trans}= 16.0 Hz), 4.57 (2 × q, H_b, J_{trans}= 16.0 Hz, J= 7.0 Hz), 8.26 (broad s, 9H, 3 × Me), 8.28 (d, 3H, J= 7.0 Hz)

Preparation of 3,3,4,4,4-pentadeuterobutan-2-one (114)

(a) Pentadeuteroethyl bromide (7.30 g) was reacted with magnesium (1.60 g) in dry ether to form the Grignard reagent. Acetaldehyde (2.90 g) was added slowly in dry ether and the reaction mixture refluxed for an hour, after which the mixture was poured onto ice/water. The precipitate was dissolved with dil. H_2SO_4, and the ethereal layer removed and dried over $MgSO_4$. After filtering, the solvent was removed at atmospheric pressure through a fractionating column and Perkin Head. The product was purified by careful distillation.

Yield: 4.15 g (83%) b.p. 100°

I.R. 3620 (w), 3340 (s), 2970 (s), 2870 (m), 2220 (m), 2080 (w), 1340 (m), 1090 (s), 910 (m)

P.M.R. 6.40 (c, 1H, C<u>H</u>-OH), 7.40 (broad s, 1H, -OH), 8.84 (d, 3H, J= 6.0 Hz)

M.S. $m^+ = 79$

(b) 3,3,4,4,4-pentadeuterobutan-2-ol (4.15 g) was oxidised in acetone using Jones reagent. The mixture was stirred for 3 hours, after which time g.l.c. analysis (column A, 80°) showed > 95% conversion to the ketone. The product was extracted according to the normal Jones oxidation procedure and dried over $MgSO_4$. The solvent was removed through a column and Perkin Head, the product being purified by distillation through a Büchi fractionating column.

Yield: 1.64 g (40%) b.p. 80°

I.R. 3000 (m), 2240 (s), 2130 (m), 2080 (w), 1710 (s), 1350 (s), 1050 (m)

P.M.R. 7.90 (s, 3H)

M.S. m/e = 77, 62, 43

Cyclobutylidene Rearrangements

Preparation of 2,2-dimethylcyclobutan-1-one

C.D.S.F. (97), (4.12 g, 13 millimole), and A.R. acetone (0.76 g, 13 millimole) were treated with KOH (1.05 g, 26 millimole) in DMSO for 4 hours. The product was distilled from the reaction vessel into a -78^{o} trap, dissolved in ether and shaken with aqueous 1 M HBF_4. Removal of the solvent gave the product.

Yield: 1.10 g (87%)

I.R. 2980 (m), 2920 (w), 2860 (w), 1780 (s), 1120 (m).

P.M.R. 7.00 (c, 2H, αCH_2), 8.15 (c, 2H, βCH_2), 8.83 (s, 6H).

Preparation of 2,2-dimethylcyclobutan-1-one tosylhydrazone

The tosylhydrazone was prepared from the cyclobutanone (1.10 g) and p-tosylhydrazine (2.09 g).

Yield: 0.90 g (30%) m.p. $153-155^{o}$

I.R. 3200 (m), 1595 (w), 1350 (s), 1165 (m).

P.M.R. ($CDCl_3$) 2.10-2.80 (c, 5H, including N-H), 7.50-8.10 (c, 7H, 2 × CH_2 and including 7.65, s, 3H), 8.90 (s, 6H).

Preparation of the Sodium Salts of the Tosylhydrazones

Equimolar quantities of the tosylhydrazone and sodium hydride (60% dispersion in oil) were mixed in dry ether and, after the initial effervescence, were refluxed for 30 minutes on a water bath. After cooling the white precipitate was filtered off, washed thoroughly with dry ether and dried under vacuum overnight. The product was used without further purification.

(i) 2,2-Dimethylcyclobutan-1-one tosylhydrazone, Sodium salt (214)

Yield: 0.56 g (99%) m.p. 180°, d

P.M.R. (D_2O) 2.60 (ABq, 4H), 7.30 (c, 2H, αCH_2), 7.78 (s, 3H), 8.40 (c, 2H, βCH_2), 9.00 (s, 6H).

(ii) 2-t-Butyl-2-methylcyclobutan-1-one tosylhydrazone, Sodium salt (217)

m.p. 180°, d

P.M.R. (D_2O) 2.55 (ABq, J= 8 Hz, 4H), 7.30 (c, 2H, αCH_2), 7.75 (s, 3H), 8.35 (c, 2H, βCH_2), 8.95 (s, 3H), 9.05 (s, 9H).

(iii) 2-Methyl-2-propylcyclobutan-1-one tosylhydrazone, Sodium salt (219)

Yield: 0.39 g (99%) m.p. 180°, d

I.R. 1650 (w), 1595 (w), 1230 (m), 1130 (s), 1090 (m).

P.M.R. (D_2O) 2.50 (ABq, 4H, J= 8 Hz), 7.27 (c, 2H, αCH_2), 7.73 (s, 3H), 8.30 (c, 2H, βCH_2), 8.60-9.50 (c, 10H, including 8.88, s, 3H).

(iv) 2-Methyl-2-phenylcyclobutan-1-one tosylhydrazone, Sodium salt (225)

Yield: 0.79 g (100%) m.p. 145°, d

I.R. 3060 (w), 1660 (m), 1603 (m), 1230 (s), 1130 (s), 1080 (s).

P.M.R. ($CDCl_3$) 2.82 (ABq, 4H, J= 9 Hz), 2.95 (s, 5H, broad) 7.50 (c, 2H), 7.83 (s, 3H), 8.25 (c, 2H), 8.78 (s, 3H).

M.S. m/e = 350, 327, 173 (Calculated for $C_{18}H_{19}N_2O_2SNa$, MW = 350).

(v) 2-(4'-Methoxyphenyl)-2-methylcyclobutan-1-one, Sodium salt (229)

Yield: 1.74 g (100%) m.p. 140°, d

I.R. 1660 (w), 1505 (m), 1250 (m), 1140 (m).

P.M.R. ($CDCl_3$) 2.30-3.50 (c, 8H), 6.35 (s, 3H, -OMe), 7.50 (c, 2H), 7.85 (s, 3H), 8.20 (c, 2H), 8.81 (s, 3H).

M.S. m^+ = 380 (Calculated for $C_{19}H_{21}N_2O_3SNa$, MW = 380).

Decomposition of the Sodium Salts, by Pyrolysis

Three methods of decomposition were used, as described in the text, and are listed below:

Method (a)

The sodium salt was mixed with about 4 times its bulk of sand, and left under vacuum overnight. The mixture was placed in a Pyrex tube having a ground-glass joint to which was attached a glass tap, also fitted with ground-glass joints. The tube was connected to a vacuum-line, via a trap, using all-glass connections - and evacuated to 0.1 torr. The tap was closed and the tube removed from the vacuum-line and partially immersed in an oil-bath maintained at 140^{o}.

After several hours liquid could be seen collecting around the cold part of the tube; the tube was removed from the oil-bath, reconnected to the vacuum-line via a -78^{o} trap and the contents of the tube distilled into the trap. The products were analysed by g.l.c.

Method (b)

The sodium salt was mixed with about 4 times its bulk of sand and left under vacuum overnight. The mixture was placed in a large Pyrex tube fitted with a ground-glass joint to which was attached a Dreschel head. One arm of the head was connected, via a cold trap, to the vacuum line whilst the other arm (that which entered the tube) was connected to a supply of dry N_2. The tube was evacuated and the N_2 supply regulated to give a slow bleed through the tube into a -78^{o} trap. The tube was immersed in the oil-bath at 140^{o}, whereupon the products of the decomposition were distilled directly into the trap.

Method (c)

The sodium salt was mixed with about 4 times its bulk of precipitated copper powder, and left under vacuum overnight. The method then proceeded exactly as Method (b).

(i) 2,2-Dimethylcyclobutanone tosylhydrazone, Sodium salt (214)

Decomposition performed using Method (a). The product was analysed by g.l.c. (column A, 70°) and found to contain two components (total yield = 27%) separated by preparative g.l.c. (column F, 70°) and shown to be:

Isopropylidenecyclopropane (215)

Yield: 53% of mixture (by N.M.R. and g.l.c. integration)

I.R. 3080 (w), 2960 (s), 1765 (w), 1420 (m).

P.M.R. 8.20 (quintet, 6H, J= 1.6 Hz), 9.02 (c, 4H, including J= 1.6 Hz).

2-cyclopropylprop-1-ene (216)

Yield: 47% of mixture

I.R. 3080 (w), 2960 (s), 1635 (w), 900 (m).

P.M.R. 5.40 (broad s, 2H), 8.36 (d, 3H, J= 1.0 Hz), 8.65 (c, 1H), 9.30-9.60 (c, 4H).

(ii) 2-t-Butyl-2-methylcyclobutanone tosylhydrazone, Sodium salt (217)

Decomposed by Method (a). G.l.c. analysis (column A, 80°) showed the presence of two components only in the product, which were identified as:

3-t-butyl-3-methylcyclobutene (75)

Yield: 1% of product

Identified by g.l.c. comparison with authentic sample.

2-(3,3-dimethylbutylidene) cyclopropane (218)

Yield: 99% of product

I.R. 3040 (w), 2955 (s), 1760 (w), 1145 (m), 988 (m).

P.M.R. 8.21 (quintet, 3H, J= 1.5 Hz), 8.70-9.40 (c, 13H including 8.89, s, 9H).

M.S. $m^+ = 124$.

(iii) 2-Methyl-2-propylcyclobutanone tosylhydrazone, Sodium salt

(a) Decomposed by both Methods (a) and (b). Total yield = 54%. G.l.c. analyses (column B, 50^o) showed similar traces for products of both methods, consisting of two components which were identified as:

3-methyl-3-propylcyclobutene (73)

Yield: 1% of product

Identified by g.l.c. comparison with authentic sample.

(2-pentylidene)cyclopropane (220)

Yield: 98% of product

I.R. 3050 (m), 2960 (s), 2880 (m), 1776 (w), 1450 (m), 1375 (m), 995 (m).

P.M.R. 7.88 (broad t, 2H, J= 6.5 Hz), 8.23 (s, 3H, with fine splitting J= 1.5 Hz), 8.51 (c, 2H), 9.06 (broad s, 4H), 9.14 (t, 3H, J= 6.5 Hz).

A further component, amounting to 1%, was unidentified.

(b) Decomposition using Method (c) gave a mixture of hydrocarbons, collected in the cold trap, and a liquid that was retained in the pyrolysis vessel. Total yield (isolated) = 87%. G.l.c. analysis

of the mixture (column B, 55°) showed five components, which were separated by preparative g.l.c. and found to be, in order of elution:

3-methyl-3-propylcyclobutene (73)

Yield: 7% of total mixture.

(2-pentylidene)cyclopropane (220)

Yield: 66% of total.

2-cyclopropylpent-1-ene (221)

Yield: 7% of total.

I.R. 3080 (m), 2960 (s), 2870 (m), 1640 (m), 1375 (w), 890 (m).

P.M.R. 5.48 (broad s, 2H), 8.00 (t, 2H, J= 8.0 Hz), 8.50 (c, 2H), 8.75 (c, 1H), 9.06 (t, 3H, J= 8.0 Hz), 9.40-9.70 (c, 4H).

(Z)- and (E)-2-cyclopropylpent-2-ene (223) and (222) respectively

Yield: 4% of total (collected as 1 fraction).

P.M.R. 4.92 (t, 1H, J= 7.5 Hz), 8.00 (c, 2H, including J= 7.5 Hz), 8.53 (s, 3H of major isomer), 8.63 (d, 3H of minor isomer, J= 1.0 Hz), 8.40-8.90 (c, 1H), 9.03 (t, 3H of minor isomer, J= 7.5 Hz), 9.08 (t, 3H of major isomer, J= 7.5 Hz), 9.40-9.70 (c, 4H).

Several further components, amounting to less than 6% of the total were unidentified.

The liquid residue in the pyrolysis vessel was identified as the azine (224):

Yield: 10% of total mixture.

I.R. 3000 (s), 2900 (m), 1710 (m), 1480 (w), 1140 (w).

P.M.R. 7.25 (c, 4H), 8.25 (c, 4H), 8.40-8.80 (c, 14H including 8.80, s, 6H), 9.06 (c, 6H).

M.S. m/e = 248, 233, 219, 124.

(iv) 2-Methyl-2-phenylcyclobutanone tosylhydrazone, Sodium salt (225)

The salt was decomposed using Method (c). Hydrocarbon product was collected in the cold trap, and a liquid remained in the pyrolysis vessel. Total, isolated yield of product: 98%. The hydrocarbon product was analysed by g.l.c. (column A, 110°) and found to contain four major components. An attempt to separate the components by preparative g.l.c. (column F, 140°) proved unsuccessful, with only acetophenone being collected from the g.l.c. This presumably was formed by oxidation of the products on the g.l.c. column.

A P.M.R. spectrum of the mixture, however, enabled the two major components to be tentatively identified, by a comparison of the N.M.R. and g.l.c. integrations and by a comparison with other spectra. These were as follows:

1-cyclopropyl-1-phenylethylene (227)

Yield: 45% of product.

Identified by the presence of two alkene proton signals at 4.79 and 5.13 τ in the P.M.R. spectrum, and by the presence of an absorbance in the I.R. spectrum at 900 cm^{-1} ($=CH_2$).

(1-phenylethylidene)cyclopropane (226)

Identified by a signal at 7.80 τ, a quintet with J= 1.5 Hz, indicative of the methyl group, and by a weak absorbance in the I.R. spectrum at 1765 cm^{-1}, attributable to the methylenecyclopropane skeleton.[129]

3-methyl-3-phenylcyclobutene (77)

Yield: 4% of total.

Identified by g.l.c. comparison with authentic sample.

The final major component (11%) was unable to be identified, though a signal at 7.55 τ (singlet) could be attributed to it.

The liquid left in the pyrolysis vessel was extracted with pentane and was identified as the azine (228).

Yield: 14% of total.

I.R. 3060 (m), 3020 (m), 1695 (m), 1450 (s), 1170 (s).

P.M.R. 2.76 (c, 10H), 7.50 (c, 4H), 8.20 (c, 4H), 8.72 (c, 6H).

M.S. m/e = 316, 158, 145.

(v) 2-(4'-Methoxyphenyl)-2-methylcyclobutanone tosylhydrazone, Sodium salt (229)

Decomposition of the salt was effected using Method (c). The products of the reaction were distilled with difficulty at 0.01 torr into a -78^{o} trap, g.l.c. analysis (column A, 130^{o}) showing two components only. The pyrolysis residues were extracted with pentane but no more product was obtained by this manner. Total yield (isolated) = 68%. The two components were identified by N.M.R. and g.l.c. integration as:

2-cyclopropyl-2-(4'-methoxyphenyl)-ethylene (231)

Yield: 73% of mixture.

The I.R. spectrum contained absorbances as 1680 and 900 that were attributable to this product. The P.M.R. spectrum contained two alkene proton signals (singlets) at 4.88 and 5.22 τ.

1-(4'-methoxyphenyl)ethylidene cyclopropane (230)

Yield: 27% of mixture.

Identified by the presence of an I.R. absorbance at 1780 cm^{-1}, and a quintet in the P.M.R. at 7.83 τ, J= 1.5 Hz.

Preparation of 1,3-dicyanoethoxy propane (1,3-DCEP)

This was prepared from propan-1,3-diol and acrylonitrile, according to the method of Bruson and Riener.[128]

b.p. 155^{o} at 0.6 torr (lit: 165^{o} (1 torr)[128])

I.R. 2260 (m), 1120 (s)

P.M.R. ($CDCl_3$) 6.2-6.55 (c, 8H), 7.35 (t, 4H, J= 6.5 Hz), 8.10 (c, 2H)

REFERENCES

1. E. Vogel, Annalen der Chemie, 1958, 615, 14.
2. E. Vogel, Angew Chem., 1954, 66, 640.
3. R. B. Woodward and R. Hoffmann, "The Conservation of Orbital Symmetry", Verlag Chemie, 1970.
4. K. Fukui, Acc. Chem. Res., 1971, 4, 57.
5. K. Hsu, R. J. Buenker and S. Peyerimhoff, J. Amer. Chem. Soc., 1971, 93, 2117.
6. W. Cooper and W. D. Walters, J. Amer. Chem. Soc., 1958, 80, 4220.
7. M. J. S. Dewar and S. Kirschner, J. Amer. Chem. Soc., 1971, 93, 4290.
8. M. J. S. Dewar and S. Kirschner, J. Amer. Chem. Soc., 1971, 93, 4292.
9. L. M. Stephenson, Jr. and J. I. Brauman, Acc. Chem. Research, 1974, 7, 65.
10. G. A. Doorakian and H. H. Freedman, J. Amer. Chem. Soc., 1968, 90, 5310.
11. J. I. Brauman and D. M. Golden, J. Amer. Chem. Soc., 1968, 90, 1920.
12. J. I. Brauman and W. C. Archie, Jr., J. Amer. Chem. Soc., 1972, 94, 4262.
13. R. E. K. Winter, Tetrahedron Letters, 1965, 1207.
14. G. A. Doorakian and H. H. Freedman, J. Amer. Chem. Soc., 1968, 90, 6896.
15. J. I. Brauman and W. C. Archie, Jr., Tetrahedron, 1971, 27, 1275.
16. R. Srinivasan, J. Amer. Chem. Soc., 1969, 91, 7557.
17. H. M. Frey, Trans. Faraday Soc., 1962, 58, 957.
18. H. M. Frey, Trans. Faraday Soc., 1963, 59, 1619.
19. H. M. Frey, Trans. Faraday Soc., 1964, 60, 83.
20. H. M. Frey, D. C. Marshall and R. F. Skinner, Trans. Faraday Soc., 1965, 61, 861.

21. H. M. Frey and D. C. Marshall, Trans. Faraday Soc., 1965, 61, 1715.

22. H. M. Frey and R. F. Skinner, Trans. Faraday Soc., 1965, 61, 1918.

23. G. R. Branton, H. M. Frey, D. C. Montague and I. D. R. Stevens, Trans. Faraday Soc., 1966, 62, 659.

24. G. R. Branton, H. M. Frey and R. F. Skinner, Trans. Faraday Soc., 1966, 62, 1546.

25. H. M. Frey, D. C. Montague and I. D. R. Stevens, Trans. Faraday Soc., 1967, 63, 372.

26. H. M. Frey, B. M. Pope and R. F. Skinner, Trans. Faraday Soc., 1967, 63, 1166.

27. H. M. Frey and B. M. Pope, Trans. Faraday Soc., 1969, 65, 441.

28. H. M. Frey and R. K. Solly, Trans. Faraday Soc., 1969, 65, 448.

29. D. Dickens, H. M. Frey and R. F. Skinner, Trans. Faraday Soc., 1969, 65, 453.

30. A. T. Cocks and H. M. Frey, J. Chem. Soc. (B), 1970, 952.

31. H. M. Frey, J. Metcalfe and J. M. Brown, J. Chem. Soc. (B), 1970, 1586.

32. H. M. Frey, J. Metcalfe and B. M. Pope, Trans. Faraday Soc., 1971, 67, 750.

33. D. Dickens, H. M. Frey and J. Metcalfe, Trans. Faraday Soc., 1971, 67, 2328.

34. R. Criegee, Angew Chem. (Int. Ed.), 1968, 7, 559.

35. H. M. Frey and R. Walsh, Chem. Reviews, 1969, 69, 103.

36. M. Pomerantz and P. H. Hartman, Tetrahedron Letters, 1968, 991.

37. C. T. Genaux, F. Kern and W. D. Walters, J. Amer. Chem. Soc., 1953, 75, 6196.

38. R. E. K. Winter and M. L. Honig, J. Amer. Chem. Soc., 1971, 93, 4616.

39. B. J. Arnold and P. G. Sammes, J. Chem. Soc. Chem. Comm., 1972, 30.

40. B. J. Arnold and P. G. Sammes, J. Chem. Soc. Chem. Comm., 1972, 1034.

41. B. J. Arnold, S. M. Mellows, P. G. Sammes and T. W. Wallace, J. Chem. Soc., Perkin I, 1974, 401.

42. C. W. Jefford, A. F. Boschung and C. G. Rimbault, Tetrahedron Letters, 1974, 3387.

43. T. Kametani, K. Ogasawara and T. Takahashi, J. Chem. Soc. Chem. Comm., 1972, 675.

44. R. Hug, H. J. Hansen and H. Schmid, Helv. Chem. Acta., 1972, 55, 10.

45. A. Arbusov, Chem. Ber., 1905, 38, 1171.

46. A. Arbusov, J. Russ. Phys. Chem. Soc., 1906, 38, 161.

47. W. R. Moser, J. Amer. Chem. Soc., 1969, 91, 1135 and 1141.

48. B. W. Peace and D. S. Wulfman, Tetrahedron Letters, 1971, 3799.

49. B. W. Peace, F. Carman and D. S. Wulfman, Synthesis, 1971, 658.

50. B. W. Peace and D. S. Wulfman, J. Chem. Soc. Chem. Comm., 1971, 1179.

51. D. S. Wulfman, B. W. Peace and E. K. Steffen, J. Chem. Soc. Chem. Comm., 1971, 1360.

52. I. D. R. Stevens, H. M. Frey and C. L. Bird, Angew Chem. (Int. Ed.), 1968, 7, 646.

53. R. J. Ellis and H. M. Frey, J. Chem. Soc., 1964, 5578.

54. J. J. Bloomfield, Tetrahedron Letters, 1968, 587.

55. G. E. Gream and S. Worthley, Tetrahedron Letters, 1968, 3319.

56. B. M. Trost, R. LaRochelle and M. J. Bogdanowicz, Tetrahedron Letters, 1970, 3449.

57. B. M. Trost and M. J. Bogdanowicz, J. Amer. Chem. Soc., 1971, 93, 3773.

58. M. J. Bogdanowicz and B. M. Trost, Tetrahedron Letters, 1972, 887.

59. B. M. Trost and M. J. Bogdanowicz, J. Amer. Chem. Soc., 1973, 95, 2040.

60. C. R. Johnson, J. F. Katekar, R. F. Huxol and E. R. Janiga, J. Amer. Chem. Soc., 1971, 93, 3771.

61. B. M. Trost, D. Keeley and M. J. Bogdanowicz, J. Amer. Chem. Soc., 1973, 95, 3070.

62. B. M. Trost and D. E. Keeley, J. Amer. Chem. Soc., 1974, 96, 1252.

63. B. M. Trost, W. L. Schinski, F. Chen and I. B. Mantz, J. Amer. Chem. Soc., 1971, 93, 676.

64. D. H. Aue, M. J. Meshishnek and D. F. Shellhammer, Tetrahedron Letters, 1973, 4799.

65. B. M. Trost and M. J. Bogdanowicz, J. Amer. Chem. Soc., 1973, 95, 5307.

66. L. Friedman and H. Schechter, J. Amer. Chem. Soc., 1960, 82, 1002.

67. R. H. Shapiro and M. J. Heath, J. Amer. Chem. Soc., 1967, 89, 5734.

68. R. H. Shapiro, Tetrahedron Letters, 1968, 345.

69. W. G. Dauben, M. E. Lorber, N. D. Vietmeyer, R. H. Shapiro, J. H. Duncan and K. Tomer, J. Amer. Chem. Soc., 1968, 90, 4762.

70. R. H. Shapiro and J. H. Duncan, Organic Syntheses, 1971, 51, 66.

71. G. Kaufman, F. Cook, H. Shechter, J. Bayless and L. Friedman, J. Amer. Chem. Soc., 1967, 89, 5736.

72. J. Meinwald and F. Uno, J. Amer. Chem. Soc., 1968, 90, 800.

73. L. M. Jackman and S. Sternhell, "Applications of N.M.R. Spectroscopy in Organic Chemistry", Pergamon, 1972.

74. J. S. Lomas, D. S. Sagatys and J. E. Dubois, Tetrahedron Letters, 1971, 599.

75. J. Hine, "Physical Organic Chemistry", McGraw-Hill.

76. W. R. Roth, J. Konig and K. Stein, Chem. Ber., 1970, 103, 426.

77. D. S. Glass, R. S. Boikess and S. Winstein, Tetrahedron Letters, 1966, 999.

78. H. M. Frey and R. Walsh, Chem. Reviews, 1969, 69, 103.

79. M. C. Flowers and H. M. Frey, J. Chem. Soc., 1961, 3547.

80. H. M. Frey and D. C. Marshall, J. Chem. Soc., 1962, 3981.

81. R. J. Ellis and H. M. Frey, J. Chem. Soc., 1964, 959.

82. R. J. Ellis and H. M. Frey, J. Chem. Soc., 1964, 4188.

83. H. M. Frey and A. Krantz, J. Chem. Soc. (A), 1969, 1159.

84. J. W. de Haan and L. J. M. van de Ven, Tetrahedron Letters, 1971, 3965.

85. J. W. de Haan and L. J. M. van de Ven, Org. Mag. Res., 1973, 5, 147.

86. D. E. Dorman, M. Jautelat and J. D. Roberts, J. Org. Chem., 1971, 36, 2757.

87. E. Lippmaa, T. Pehk, K. Anderson and C. Rappe, Org. Mag. Res., 1970, 2, 109.

88. G. C. Levy and G. L. Nelson, "Carbon-13 N.M.R. for Organic Chemists", Wiley, 1972.

89. D. M. Grant and B. V. Cheney, J. Amer. Chem. Soc., 1967, 89, 5315.

90. W. R. Woolfenden and D. M. Grant, J. Amer. Chem. Soc., 1966, 88, 1496.

91. L. M. Jackman and R. H. Wiley, J. Chem. Soc., 1960, 2881.

92. F. C. Stehling and K. W. Bartz, Anal. Chem., 1966, 38, 1467.

93. S. W. Tobey, J. Org. Chem., 1969, 34, 1281.

94. D. J. Frost and J. P. Ward, Tetrahedron Letters, 1968, 3779.

95. R. B. Bates, A. D. Brewer and B. R. Knights, Tetrahedron Letters, 1968, 6163.

96. G. G. Cárdenas, Tetrahedron Letters, 1969, 4013.

97. G. G. Cárdenas, J. Org. Chem., 1971, 36, 1631.

98. E. L. Eliel, N. L. Allinger, S. J. Angyal and G. A. Morrison, "Conformational Analysis", Interscience.

99. S. Winstein and N. J. Holness, J. Amer. Chem. Soc., 1955, 77, 5562.

100. D. S. Noyce and L. J. Dolby, J. Org. Chem., 1961, 26, 3619.

101. O. S. Tee, J. Amer. Chem. Soc., 1969, 91, 7144.

102. O. S. Tee and K. Yates, J. Amer. Chem. Soc., 1972, 94, 3074.

103. F. O. Rice and E. Teller, J. Chem. Phys., 1938, 6, 489.

104. L. Libit and R. Hoffmann, J. Amer. Chem. Soc., 1974, 96, 1370.

105. W. J. Hehre, L. Radom and J. A. Pople, J. Amer. Chem. Soc., 1972, 94, 1496.

106. P. von R. Schleyer and C. W. Woodworth, J. Amer. Chem. Soc., 1968, 90, 6528.

107. K. N. Houk, J. Amer. Chem. Soc., 1973, 95, 4092.

108. IUPAC Rules, J. Org. Chem., 1970, 35, 2849.

109. W. R. Bamford and T. S. Stevens, J. Chem. Soc., 1952, 4735.

110. J. Meinwald, J. W. Wheeler, A. A. Nimetz and J. S. Liu, J. Org. Chem., 1965, 30, 1038.

111. F. T. Bond and D. E. Bradway, J. Amer. Chem. Soc., 1965, 87, 4977.

112. G. Maier, Tetrahedron Letters, 1965, 3603.

113. K. B. Wiberg, G. J. Burgmaier and P. Warner, J. Amer. Chem. Soc., 1971, 93, 246.

114. K. B. Wiberg, J. E. Hiatt and G. Burgmaier, Tetrahedron Letters, 1968, 5855.

115. J. R. Chapman, Tetrahedron Letters, 1966, 113.

116. B. Singh, J. Org. Chem., 1966, 31, 181.

117. G. Maier and M. Strasser, Tetrahedron Letters, 1966, 6453.

118. M. Rey, U. A. Huber and A. S. Dreiding, Tetrahedron Letters, 1966, 3583.

119. R. D. Miller and D. L. Dolce, Tetrahedron Letters, 1973, 4403.

120. A. S. Kende and E. E. Riecke, J. Chem. Soc., Chem. Comm., 1974, 10, 383.

121. A. Nickon, F. Huang, R. Weglein, K. Matsuo and H. Yagi, J. Amer. Chem. Soc., 1974, 96, 5264.

122. W. Kirmse, "Carbene Chemistry", Academic Press, 1971.

123. A. I. Vogel, "Practical Organic Chemistry", Longman, 1972.

124. N. E. Searle, Organic Syntheses, Coll. Vol. 4, 424.

125. J. Meinwald, J. Crandall and W. E. Hymans, Organic Syntheses, 1965, 45, 77.

126. J. C. H. Hwa and H. Sims, Organic Syntheses, 1961, 41, 49.

127. G. A. Olah and H. W. Quinn, J. Inorg. Nucl. Chem., 1960, 14, 295.

128. H. A. Bruson and T. W. Riener, J. Amer. Chem. Soc., 1943, 65, 23.

129. H. E. Simmons, E. P. Blanchard and H. D. Hartzler, J. Org. Chem., 1966, 31, 295.