π-ROUTES TO CARBONIUM IONS

A Thesis
Presented for the Degree of
Doctor of Philosophy

in

The University of Adelaide

by

Peter Howard Ferber B.Sc.(Hons.)
Department of Organic Chemistry

1979

CONTENTS

		Page
SUMMARY		iv
STATEMENT		v
ACKNOWLEDGEMENTS		vi
INTRODUCTION		1
CHAPTER 1.	The solvolysis of 3-(cyclohex-1'-enyloxy)propyl *p*-nitrobenzenesulphonate in buffered ethanol and trifluoroethanol.	33
CHAPTER 2.	The synthesis of derivatives of 4-(2'-oxacyclohex-1'-enyl)butanol	50
CHAPTER 3.	The solvolysis of 3-(cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate in trifluoroethanol and hexafluoropropan-2-ol and the solvolysis of 4-pentenyl *p*-nitrobenzenesulphonate in hexafluoropropan-2-ol	60
CHAPTER 4.	The solvolysis of 4-phenylbutyl *p*-nitrobenzenesulphonate in trifluoroethanol and hexafluoropropan-2-ol	74
CHAPTER 5.	The solvolysis of 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate in trifluoroethanol and hexafluoropropan-2-ol	81
CHAPTER 6.	The solvolysis of 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate in trifluoroethanol and hexafluoropropan-2-ol	103
CHAPTER 7.	Tetracyanoethylene adducts of bicyclo[6.3.0]-undeca-2,4,6,8(9)-tetraene and bicyclo[6.4.0]-dodeca-2,4,6,8(9)-tetraene	122

../

Table of Contents (cont.)

	Page
EXPERIMENTAL SECTION	144
General	145
Work described in Chapter 1	154
Work described in Chapter 2	159
Work described in Chapter 3	172
Work described in Chapter 4	180
Work described in Chapter 5	182
Work described in Chapter 6	188
Work described in Chapter 7	195
REFERENCES	199

SUMMARY

The extent of π-bond participation during solvolysis in 2,2,2-trifluoroethanol and 1,1,1,3,3,3-hexafluoropropan-2-ol for substrates with π-bonds in the 4,5 or 5,6 position relative to the leaving group have been studied.

The following p-nitrobenzenesulphonates were studied: 3-(cyclohex-1'-enyloxy)propyl (chapter 1), 3-(cyclohex-1'-enyl)propyl (chapter 3), 4-pentenyl (chapter 3), 4-phenylbutyl (chapter 4), 3-cyclooctatetraenyl-propyl (chapter 5) and 4-cyclooctatetraenylbutyl (chapter 6). With one possible exception, all substrates showed a marked increase in the extent of π-bond participation (as evidenced by both kinetic and product studies) in the above solvents compared to their solvolysis in acetic acid.

In chapter 2, the synthesis of 4-(2'-oxacyclohex-1'-enyl)butanol and some of its derivatives are described.

The isolation and characterization of bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (chapter 5), bicyclo[6.4.0]dodeca-2,4,6,8(9)-tetraene (chapter 6) and their tetracyanoethylene adducts (chapter 7) are also reported.

STATEMENT

This thesis contains no material previously submitted for a degree or diploma in any university, and to the best of my knowledge and belief, contains no material previously published or written by another person except where due reference is made in the text.

P.H. Ferber

ACKNOWLEDGEMENTS

I wish to thank sincerely Dr. G.E. Gream for his help, guidance and encouragement during his supervision of this work. I would also like to extend my thanks to those members of the department, in particular the members of Lab. 2, who have assisted me during the course of my stay here. I am grateful to Dr. H. Grant, R.D. Wagner, R. Wallis and C. Easton, who gave up their time to record the ^{13}C and 80 MHz ^{1}H n.m.r. spectra reported in this thesis; the bulk of this task was performed by the two gentlemen named last.

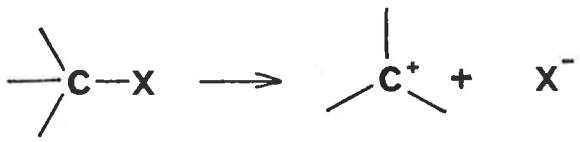
The research described in this thesis was carried out during the tenure of a Commonwealth Postgraduate Research Award, which I gratefully acknowledge.

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

INTRODUCTION

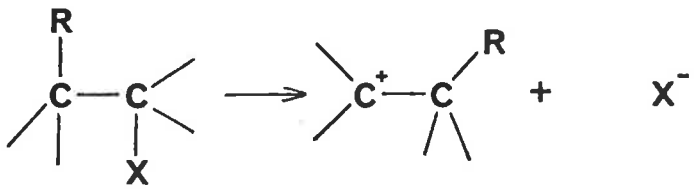
Three routes have been used to generate carbocations (or ion-pairs*) by solvolysis:[1-3]

(i) the direct route i.e. the heterolysis of a C-X bond (where X is the leaving group), where the positive charge is located on the carbon atom which bore the leaving group (Equation 1).



(1)

(ii) the σ-route i.e. the positive charge is found on a carbon atom other than that which bore the leaving group; the migrating group does so by transfer of its bonding σ electrons (Equation 2).



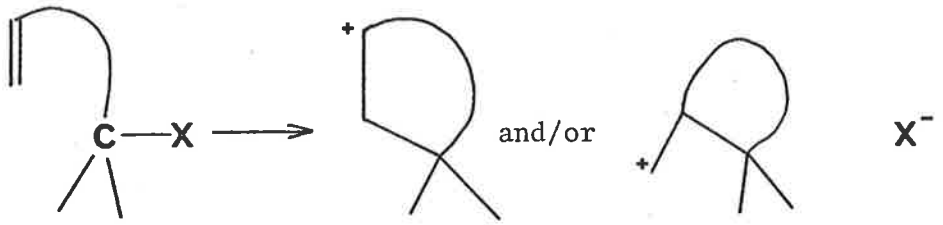
(2)

(iii) the π-route i.e. π-electrons in a multiple bond (not attached to the carbon bearing the leaving group) form a new carbon-carbon σ-bond (Equation 3). Again the carbon bearing the positive

---

* Recently, ion-pairs have been shown to be of critical importance for every solvolysis reaction and not just a few special cases.[4-8]

charge is not that which bore the leaving group.



(3)

The σ and π-routes are examples of neighbouring group participation by σ and π-bonds respectively; neighbouring group participation by a substituent may be defined as stabilization of a transition state or intermediate by bonding between the substituent and the reaction centre.*[4,9] If such participation leads to enhanced reaction rate, the substituent is said to provide 'anchimeric assistance'.[9,10] The term 'intramolecular catalysis'[11] is also widely used to describe neighbouring group effects, but this term strictly should be applied only to reactions in which the neighbouring group is regenerated in the product.

As the subject of this thesis is primarily concerned with π-routes to carbonium ions, a brief review of π-bond participation will be presented.

Neighbouring group participation by π-bonds

The criteria that have been used to detect π-bond participation are (i) a solvolysis rate which is greater that that found for an

---

* Hyperconjugation is regarded as a separate phenomenon.[4,9]

analogous saturated compound, (ii) the formation of cyclized products or intermediates and (iii) stereochemical results that cannot otherwise be explained.

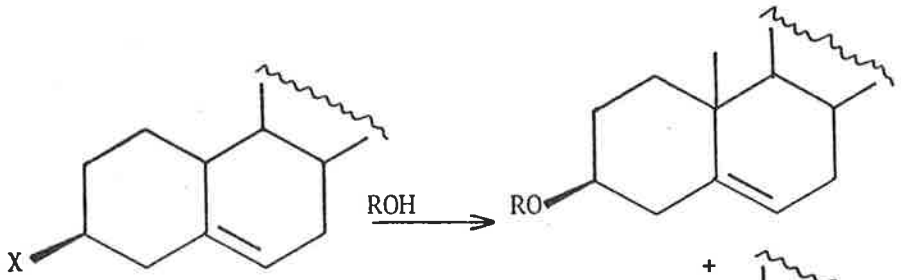
In the last 35 years, intramolecular participation by π-bonds separated from the leaving group by one or more carbon atoms has been the focus of extensive research.*[1-3,10,12-118] Neighbouring group participation by carbon-carbon double bonds is of importance in biological chemistry[119-122] and is becoming increasingly synthetically useful.[122-125]

The earliest examples of π-bond participation were found in the reactions of allylic[12,20-23] and benzylic systems.[12,24] In such cases, participation takes the form of conjugative stabilization of any developing positive charge in the transition state.

Another type of participation by carbon-carbon double bonds is observed when the double bond is in the 3,4 position relative to the leaving group (termed 'homoallylic').[12-14,15a,16-18,25-33,53] The earliest reported examples of homoallylic participation were found for 3-β-cholesteryl derivatives (1). Shoppee,[28] and later Winstein,[32] found that these derivatives (1) solvolysed to give products with

---

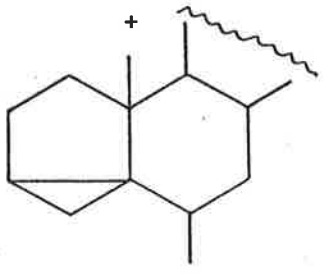
* As yet, no comprehensive reviews of this subject have appeared; reviews concerning participation by carbon-carbon double bonds,[18] homoallylic double bonds,[13,14,15a,16] β-arylalkyl systems[12,15b] and carbon-carbon triple bonds[19] have appeared, however. In addition, annual review articles dealing with π-bond participation are also available.[17]



(1)

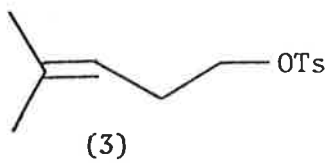
X = Cl or -OTs

-OTs = $-OSO_2C_6H_4CH_3$

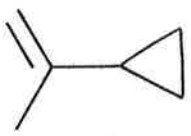


(2)

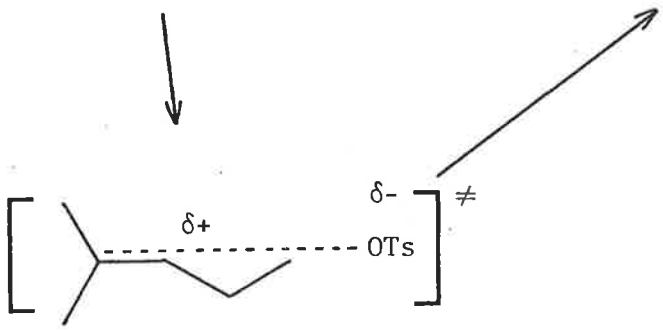
retention of configuration at the 3 position; 3α,5-cyclocholestane derivatives (2) were also isolated. The solvolysis of (1) was also found to be somewhat faster than the corresponding saturated compound. These observations could only be explained in terms of participation by the π-electrons of the 5,6 double bond with the centre of ionization. A further example of homoallylic participation is afforded by the acetolysis of 4-methylpent-3-enyl *p*-toluenesulphonate (3),[33] which proceeds 1200 times faster than that of ethyl *p*-toluenesulphonate and yields 2-cyclopropylpropene (4) in addition to 4-methylpent-3-enyl acetate (5).[33]



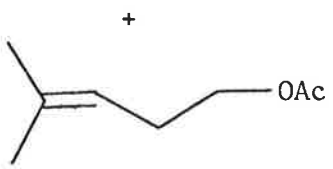
(3)



(4)



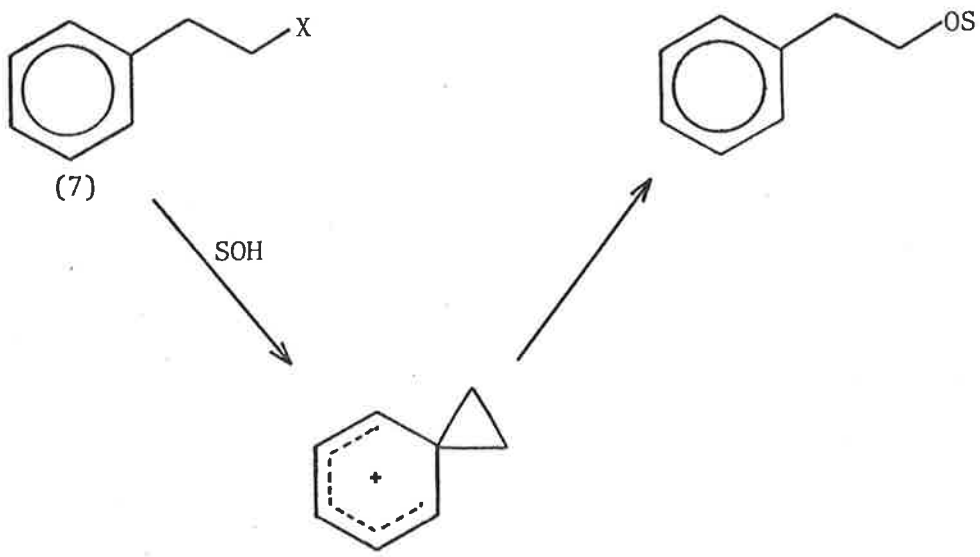
(6)



(5)

Participation by the double bond *via* the transition state (6) is postulated to account for these observations.[13,14,33]

β-Arylalkyl derivatives, the aromatic equivalent of homoallylic systems, have been the subject of many investigations.*[10,12,15b,34-41,43-52] There is extensive evidence for aryl group participation during the solvolysis of 2-phenylethyl derivatives (7);[12,15b] the phenonium ion (8) is the postulated intermediate.[12,15b]



(7) (8)

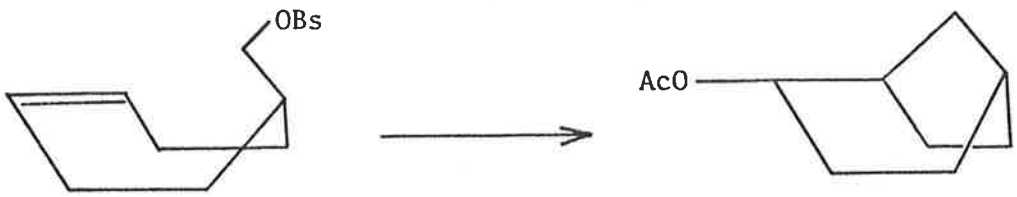
Participation by π-bonds in the 5,6 position relative to the leaving group

The participation by remote double bonds was first reported by Le Ny;[91] cyclohept-4-enylmethyl *p*-bromobenzenesulphonate (9) was found to undergo acetolysis 30 times faster than its corresponding saturated

---

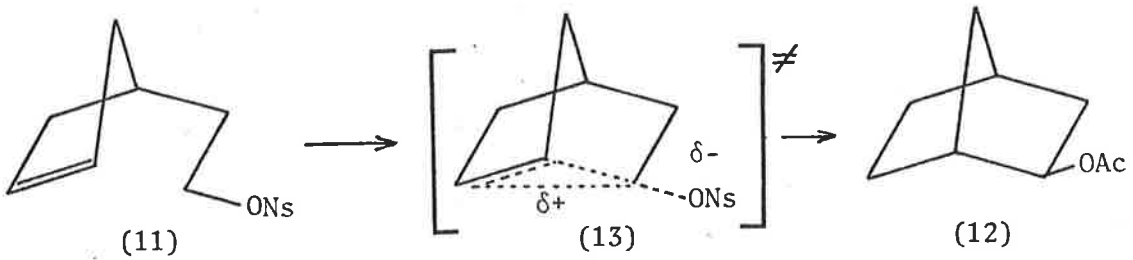
* This subject has been recently reviewed.[15b]

derivative to form at least 90% *endo*-2-bicyclo[3.2.1]octyl acetate (10).[91]



(9) (10)

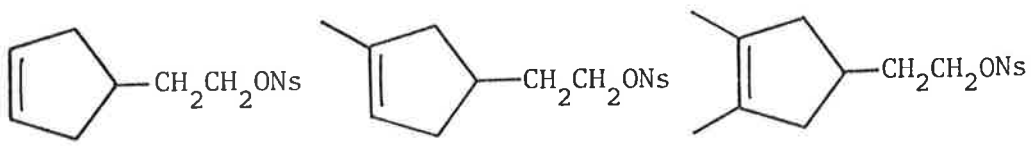
-OBs = $-OSO_2C_6H_4Br$ -OAc = $-OCOCH_3$



(11) (13) (12)

In 1961, Lawton[92] reported that 2-(cyclopent-3'-enyl)ethyl *p*-nitrobenzenesulphonate (11) undergoes acetolysis 95 times faster than the analogous saturated compound and yields *exo*-norbornyl acetate (12) almost exclusively.* This result provided a new route to the norbornyl

-ONs = $-OSO_2C_6H_4NO_2$



(11) (14) (15)

$\frac{k_{unsat}}{k_{sat}}$	87	605	3315

* Bartlett and co-workers[57,101-103] have independently reported similar results.

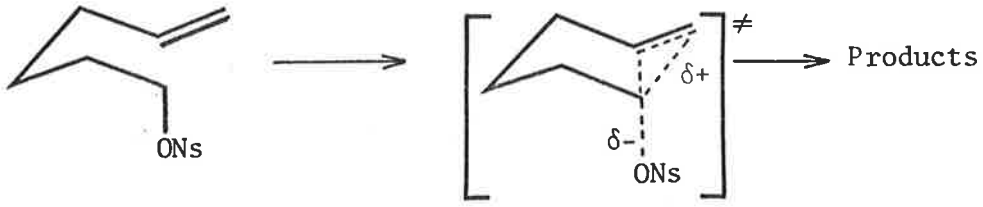
cation, the postulated intermediate, which was the centre of a major controversy which was starting at that time.[108]

Bartlett and Sargent have proposed the symmetric transition state (13) for the solvolysis of (11).[101] They argued that the cumulative rate enhancement (k_{unsat}/k_{sat}*) for the mono- and dimethyl derivatives [(14) and (15) respectively] was convincing evidence for a symmetric transition state (13).[101] Such cumulative acceleration by alkyl substituents has been observed for the electrophilic addition to olefins by reagents such peracids,[126,128,129] arylsulphenyl chlorides,[126,127,130-132] and for ionic bromination;[126,127,133-138] all of these additions are known to proceed *via* 3-membered bridged intermediates or transition states.[126,127] This argument has also been used to determine the mode of addition of carbenes to olefins.[126,139] On the other hand, for the acid catalysed hydration of simple alkenes, where the rate determining step is known to be the addition of a proton to a double bond to form a classical carbonium ion, a very different effect of substitution is observed.[126,127,137,140-142] Because the charge is localized on one carbon atom of the double bond, further substitution at the less substituted end of the double bond does not produce an increase in the rate of hydration.[101,126,127,137,140-142]

The simplest example of participation by a double bond in the 5,6 position from the leaving group is afforded by 5-hexenyl *p*-nitrobenzenesulphonate (16), which solvolyses in buffered acetic acid

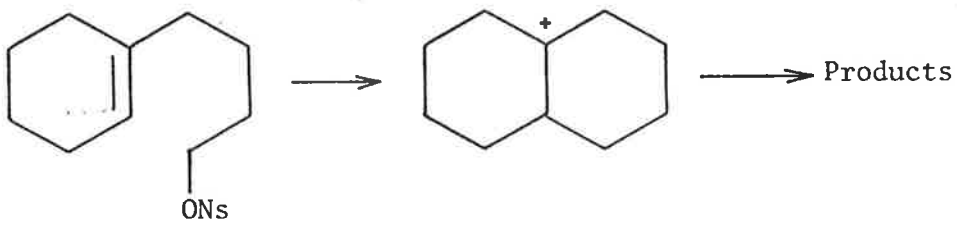
---

* This expression will be used frequently in this thesis; k_{unsat} and k_{sat} are the rate constants for the solvolysis of the relevant unsaturated substrate and its corresponding saturated derivative, respectively.



(16) (17)

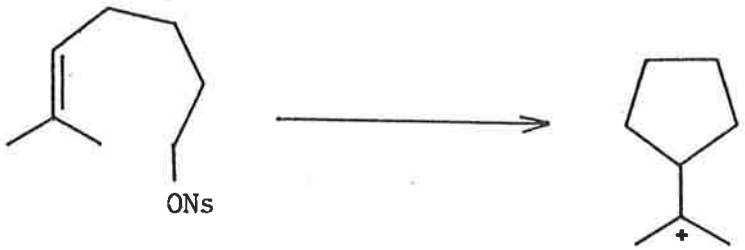
1.49 times faster than hexyl *p*-nitrobenzenesulphonate to give 16.3% yield of cyclized products.[60] Bartlett and co-workers[60] have postulated that double bond participation, in this case, proceeds through the transition state (17). As no products with 5-membered rings were detected, the transition state (17), as expected, leads to the formation of positive charge on the secondary carbon rather than the primary carbon.[60] Similarly, the acetolysis of 4-(cyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (18) proceeds 46 times faster than the



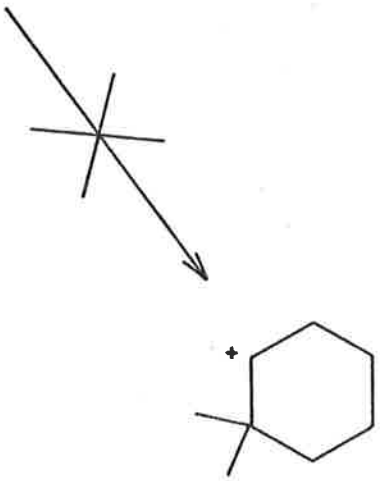
(18)

corresponding saturated derivative and gives 98.5% cyclized products;[1] no products containing 5-membered rings were detected.[1]

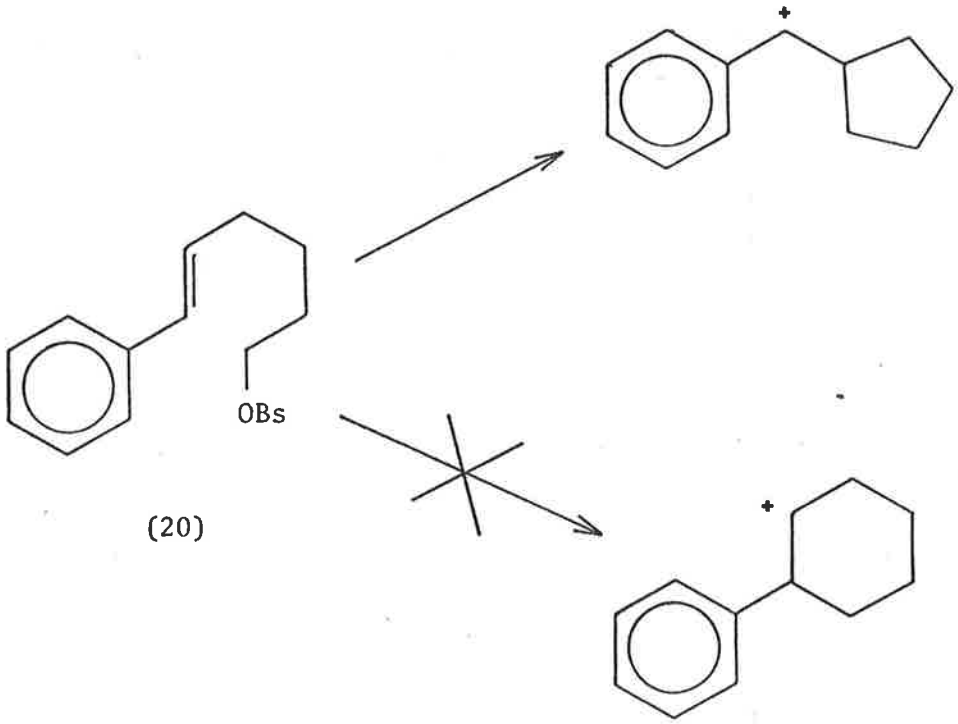
There have been examples reported where the cyclization of 5,6 unsaturated compounds has been found to result in the formation of 5-membered rings instead of the more usual 6-membered ring.[61,104] Johnson and Owyang[61] showed that the solvolysis of 6-methylhept-5-enyl *p*-nitrobenzenesulphonate (19) gave products derived from the more stable tertiary carbonium ion rather than the secondary carbonium ion. Similarly, Roman and Closson[104] have reported that the acetolysis of



(19)



6-phenylhex-5-enyl *p*-bromobenzenesulphonate (20) gave products exclusively derived from the more stable benzylic carbonium ion. It would appear that in both cases, the increased strain introduced by the

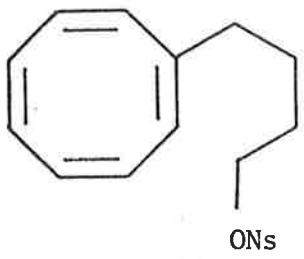


(20)

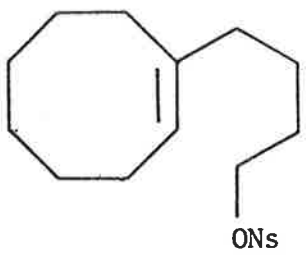
formation of 5-membered rings is more than offset by the formation of the more stable carbonium ions.

Examples of preferential formation of 5-membered rings from polyene cyclizations have been reported by Johnson and co-workers [125,143-145] as part of their work on biomimetic cyclizations.

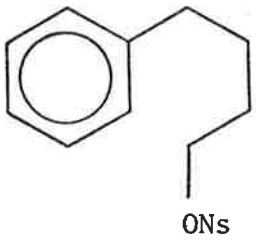
Earlier work in this department has shown that 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) solvolyses in buffered acetic acid 1.59 times faster than its corresponding saturated derivative to give 43% cyclized products.[53] The ester (21) is 53 times less



(21)



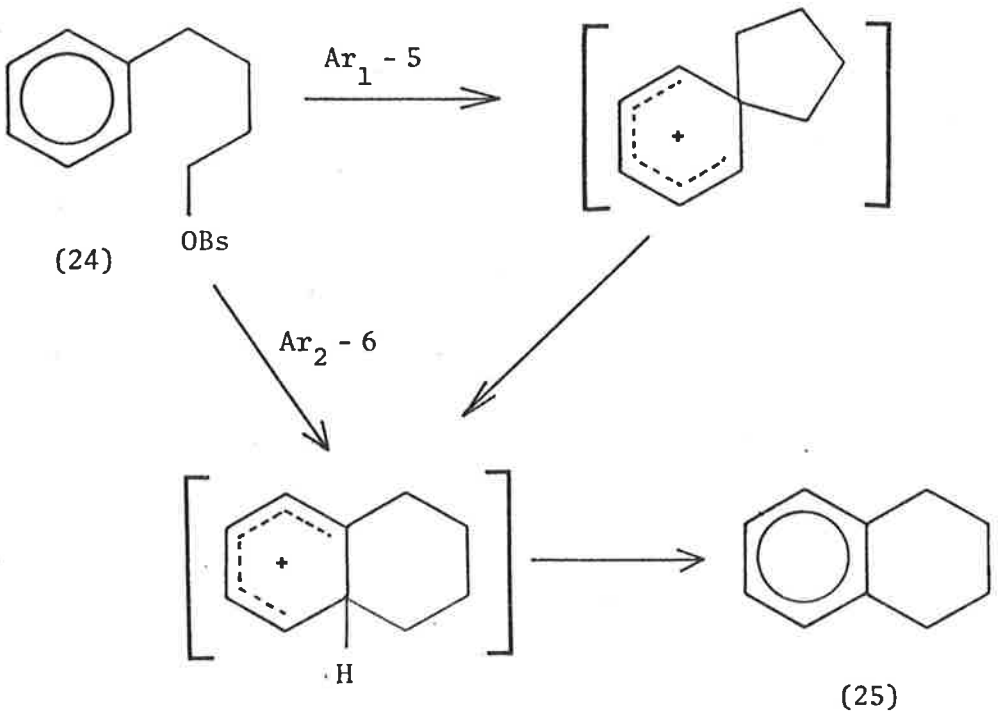
(22)



(23)

reactive, in acetic acid, than 4-(cyclooct-1'-enyl)butyl *p*-nitrobenzenesulphonate (22) but 1.8 times more reactive than 4-phenylbutyl *p*-nitrobenzenesulphonate (23).[53]

The solvolysis of 4-arylbutyl derivatives, the aromatic equivalent of substrates with a double bond in the 5,6 position, was first reported by Winstein and Heck;[109] these workers reported that 4-phenylbutyl



(24)

(25)

p-bromobenzenesulphonate (24) solvolyses in acetic acid at 0.98 times that of butyl *p*-bromobenzenesulphonate and gives only 4.9% cyclized product [tetralin (25)] in buffered acetic acid. Not surprisingly, the introduction of electron donating substituents enhances the extent of aryl participation.[109-111] More recently, Jackman and Haddon[112] and Gates *et al.*[113] have independently shown that for substituted 4-phenylbutyl *p*-bromobenzenesulphonates, participation proceeds by both Ar_1-5 and Ar_2-6 pathways;* the latter being inherently preferred.[112]

π-Bonds in the 4,5 position from the leaving group

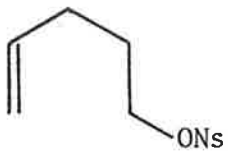
In contrast to double bonds situated in the 3,4 or 5,6 position relative to the leaving group, those in the 4,5 position, with few exceptions,[29,42,75,76] show no tendency to participate during solvolysis in the usual solvolysis solvents i.e. ethanol, acetic acid or formic acid.[2,18,30,53,55-61,95]

Two examples are 4-pentenyl *p*-nitrobenzenesulphonate (26)[60] and 3-(cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate (27)[2] which solvolyse in buffered acetic acid at 0.7 and 0.87 times that of the corresponding saturated derivatives, respectively;** in both cases no cyclized products were detected. A further example is afforded by

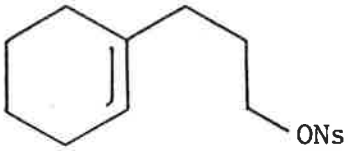
---

* This notation was proposed by Winstein and is explained in reference 109.

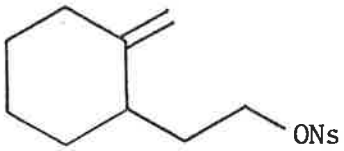
** *n*-Hexyl *p*-nitrobenzenesulphonate was used as the reference compound for the 4-pentenyl derivative.[60] The rate retardation is attributed to the adverse inductive effect of the double bond.[1,2,30,60,104]



(26)



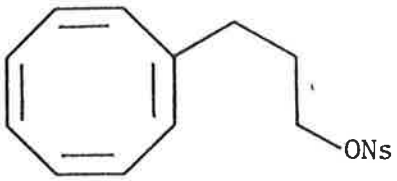
(27)



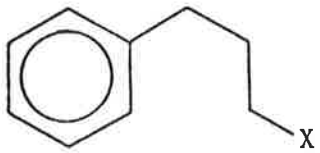
(28)

2-(2'-methylenecyclohexyl)ethyl *p*-nitrobenzenesulphonate (28) which also solvolyses in acetic acid without double bond participation.[2]

Work in this department[53] has shown that 3-cyclooctatetraenyl-propyl *p*-nitrobenzenesulphonate (29) solvolyses in buffered acetic acid at 0.6 times the rate of the corresponding saturated derivative; only 1.6% cyclized products were obtained.*[53]



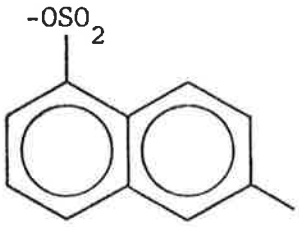
(29)



(30)

X = OBs, ONs or OMnS

-OMnS =



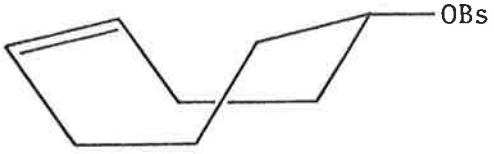
---

* The ester (29) also has a double bond in the 5,6 position which might account for the small amount of cyclized material. The cyclized product was not identified in the work referred to above;[53] in the present work, however, this cyclized product was fully characterized (Chapter 5).

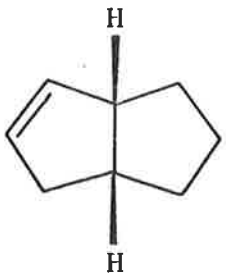
3-Phenylpropyl arenesulphonate derivatives (30), the aromatic analogue of substrates with a double bond in the 4,5 position relative to the leaving group, solvolyse in acetic acid, formic acid and trifluoroacetic acid without aryl participation.[52,53,109]

The lack of neighbouring group participation by double bonds in the 4,5 position relative to the leaving group has been attributed to the difficulty of obtaining the required transition state geometry.[2] From models it can be seen that the carbon bearing the leaving group cannot closely approach the double bond in the plane of the p orbitals without introducing strain energy.[2]

Although the lack of participation by double bonds in the 4,5 position relative to the leaving group is general, there are examples of participation in such cases where physical constraints or non-bonded interactions result in the double bond and the carbon bearing the leaving group being in close proximity to each other.[29,42] Cope and Peterson[29] have demonstrated double bond participation during the acetolysis of 4-cyclooctenyl *p*-bromobenzenesulphonate (31); *cis*-bicyclo[3.3.0]oct-

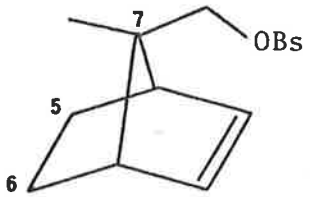


(31)

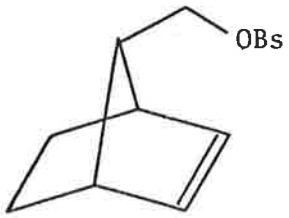


(32)

2-ene (32) comprised 64% of the olefinic products, and 80% of the acetate products were bicyclic.[29] In this case, double bond participation is attributed to the close proximity of the double bond to the carbon bearing the leaving group as a result of the tub shape of one of the cyclooctene conformers (31).[29] Berson and co-workers[42] have shown that the ester (33) undergoes acetolysis with double bond participation to give a 45% yield of cyclized products. In this case double bond participation is attributed to the close proximity of



(33)



(34)

the carbon bearing the leaving group with the π-orbitals of the double bond; this close proximity is the result of non-bonded interactions between the 7-*anti* methyl group and the *exo* hydrogens at C5 and 6.[42] As expected, the corresponding derivative without the methyl group i.e. (34) solvolyses in acetic acid without double bond participation.[55,56]

An example of the double bond of an enol ether in the 4,5 position relative to the leaving group, participating during solvolysis is also known (see p. 17).[75,76]

π-Bonds in the 6,7 position from the leaving group

Participation by double bonds in a 6,7 position from the leaving group has been observed in only a few systems;[58,64-68,70-74] in non-rigid systems, however, the extent of participation is less than that for analogous systems with the double bond in the 5,6 position.[58,68,70]

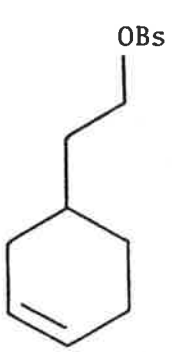
The effect of substituents on the participating double bond

There have been many examples reported where the extent of double bond participation is increased by alkyl substitution of the double bond.[1,61,70,81,88,90,101] The work of Bartlett and Sargent concerning the solvolysis of mono- and dimethyl substituted cyclopent-3'-enylethyl *p*-nitrobenzenesulphonates [(14) and (15)] is an example (see earlier).[101] A further example is afforded by the comparison of the acetolysis of 4-(cyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (18)[1] with that of the 5-hexenyl derivative (16)[60] (see earlier); a much greater rate enhancement and a higher percentage of cyclized products is observed for the more substituted double bond.[1,60] Felkin and Lion[88] have shown that 2-(4'-methylcyclohex-3'-enyl)ethyl *p*-bromobenzenesulphonate (36) solvolyses 6.8 times faster than the corresponding unsubstituted ester (35).

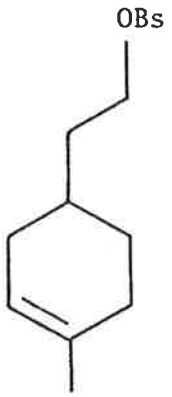
The increased degree of participation for the more substituted double bonds is attributed to the greater nucleophilicity of those bonds and the greater stabilization of positive charge in the transition state.*[87,88]

---

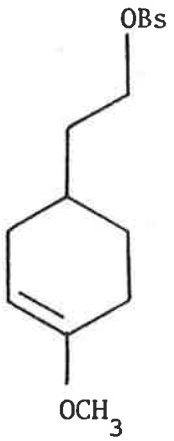
* It has also been demonstrated that the greater the substitution of a double bond the faster it reacts with various electrophiles such as peracids,[126,128,129] dibromocarbene,[126,139] arylsuphenyl chlorides[126,127,130-132] and the faster the rate of ionic bromination of the olefin.[126,127,133-138]



(35)

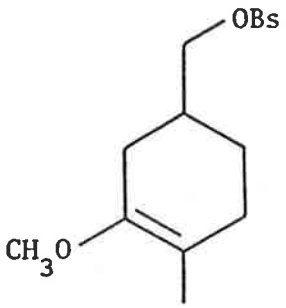


(36)

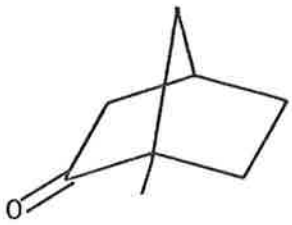


(37)

As expected, the double bond of enol ethers, where any developing positive charge in the transition state can be stabilized by delocalization on oxygen, participate in solvolysis to a greater extent than analogous double bonds without the oxygenated substituent.[75,76,87,88] Felkin and Lion have shown that 2-(4'-methoxycyclohex-3'-enyl)ethyl *p*-bromobenzenesulphonate (37) solvolyses in buffered acetonitrile 97 times faster than the corresponding unsubstituted sulphonate ester (35).[87,88] (3-Methoxy-4-methylcyclohex-3-enyl)methyl *p*-bromobenzenesulphonate (38), where the double bond is in the 4,5 position relative to the leaving group, solvolyses in acetonitrile buffered with triethylamine to give, after acidic hydrolysis, a 12% yield of 1-methylnorcamphor (39).[75,76] In this case, the combined electron donating effects of the methyl and methoxy groups provide sufficient enhancement of the nucleophilicity of the double bond and stabilization of the positive charge in the transition state to cause solvolytic ring closure in this

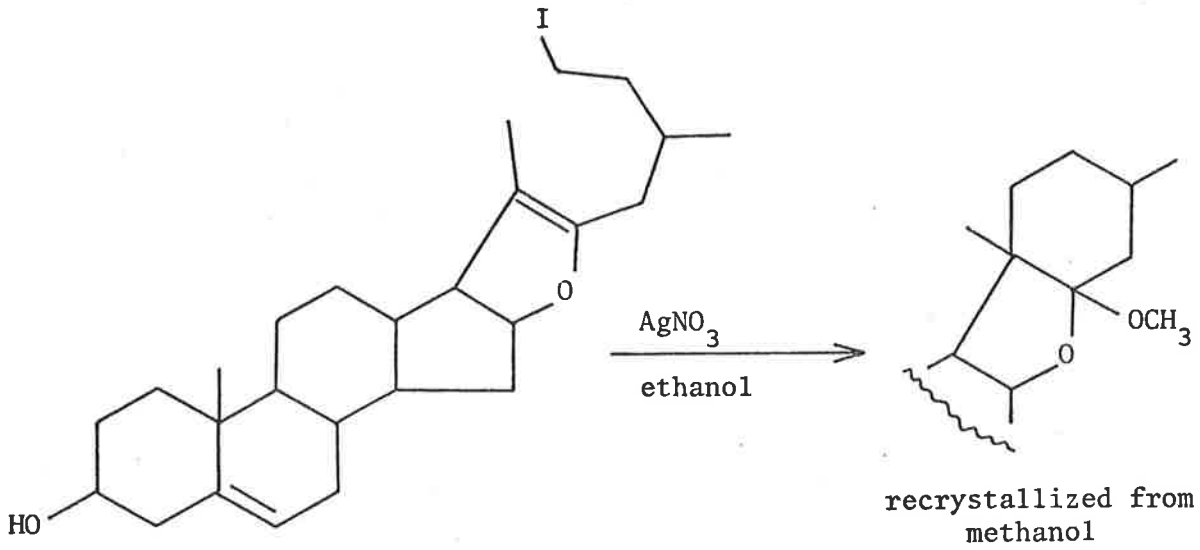


(38)



(39)

otherwise unfavourable system.[75,76] A further example of participation by the double bond of an enol ether is provided by the *pseudo*-sapogenin (40), which cyclizes in aqueous ethanol containing silver nitrate to give the cyclized product (41) after recrystallization from methanol.[146]



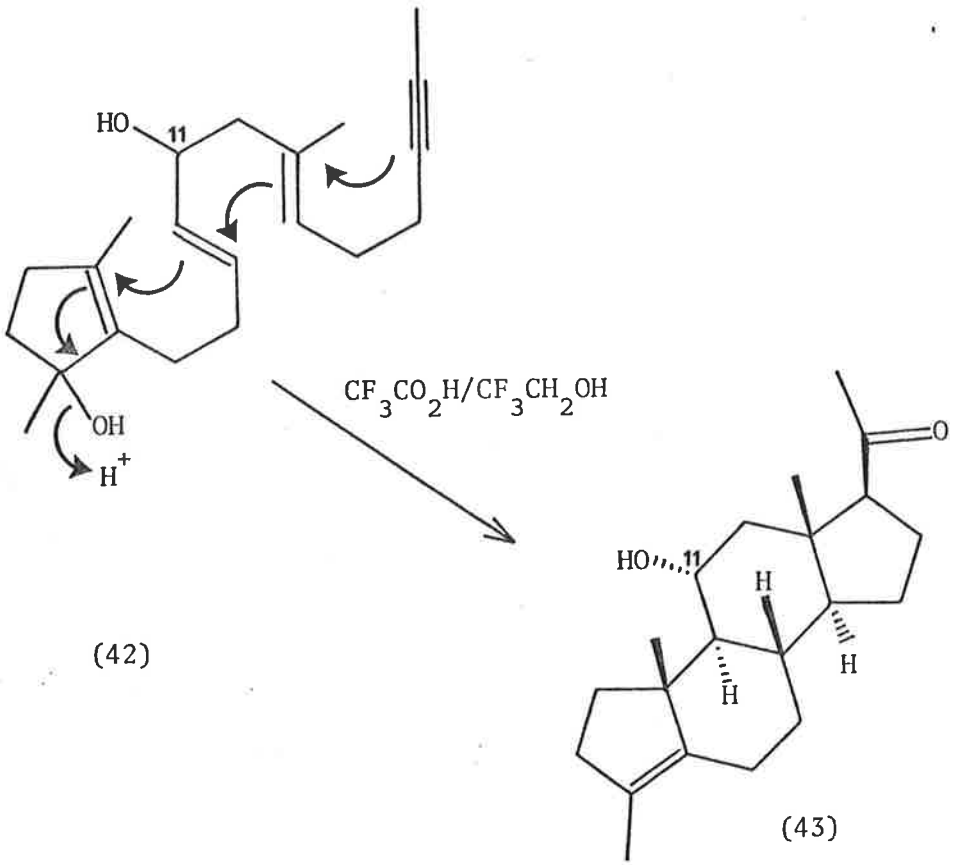
recrystallized from methanol

(40) (41)

Examples of participation by the enol tautomers of ketones[105-107] and homoallylic participation by an enol ether[31] also have been reported.

Use of π-bond participation in synthesis

π-Bond participation has recently found use in synthesis. One example is that of Johnson and co-workers[144] who have shown that the monocyclic tetraene (42) cyclizes to give stereospecifically the tetracyclic product (43) and its enantiomer in 40% yield; higher yields are obtained in the absence of the hydroxyl at C_{11}.[144] The tetracyclic product (43) might be a useful intermediate in the preparation of cortisone.

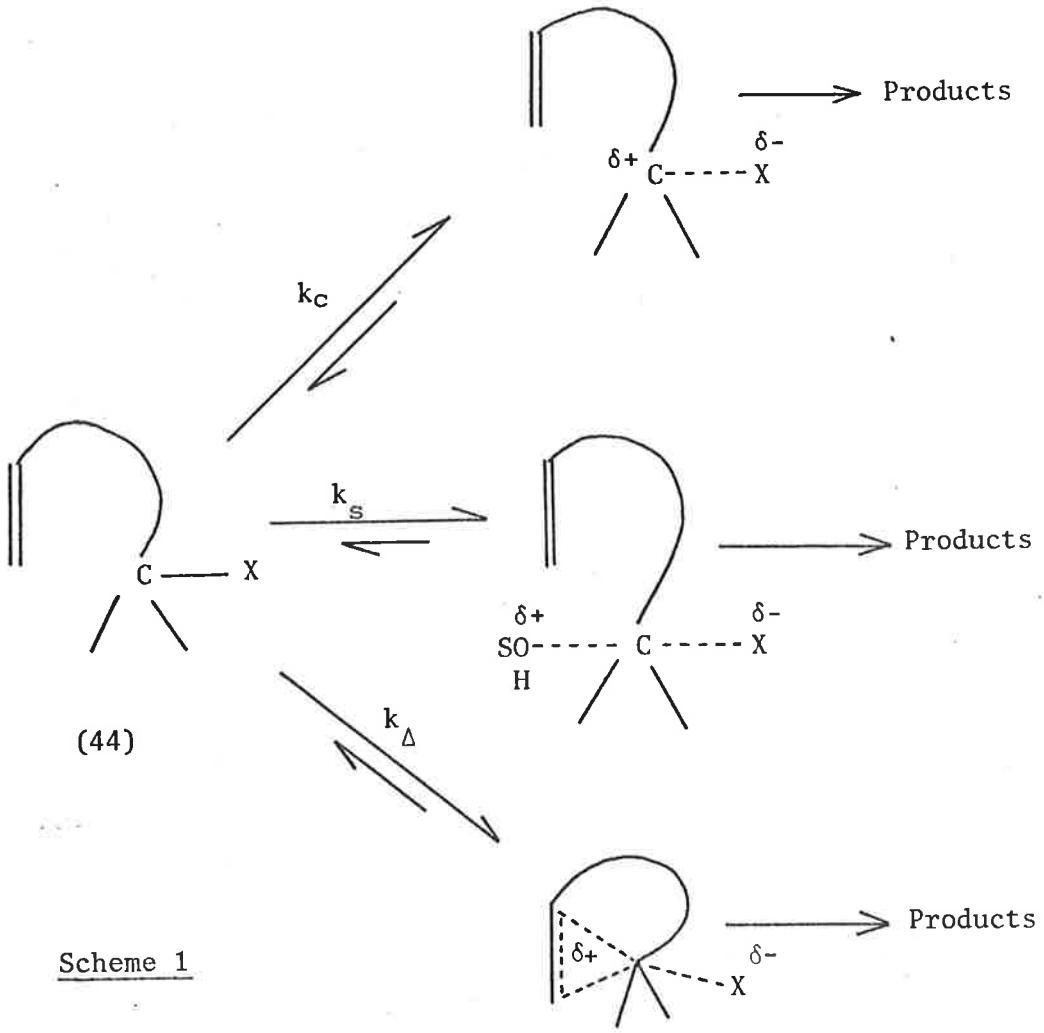


(42)

(43)

Solvent nucleophilicity and ionizing power

The solvolysis, in solvent SOH, of a substrate which possesses a π-bond separated from the carbon bearing the leaving group by one or more carbon atoms e.g. (44) may proceed by one or more possible mechanisms (Scheme 1.).[4,9,148] If, in the rate determining step, the solvent is nucleophilically partially bonded (as distinct from general electrostatic solvation) to the carbon which bore the leaving group, the solvent is said



Scheme 1

to provide nucleophilic solvent assistance and is denoted k_s.[4,147] A competing mechanism, denoted k_Δ, involves partial or complete bonding between the double bond and the carbon which bore the leaving group in the rate determining step.[4,9] Naturally, other bonds, atoms or groups might also participate in the rate determining step, so that there may be more than one k_Δ pathway. Ionization without nucleophilic solvent assistance or neighbouring group participation to give an ion-pair or free carbonium ion is denoted k_c.[9,148] According to current theory* k_c is only important for tertiary substrates and a few secondary substrates where k_s, k_Δ and elimination are disfavoured.[9,34,37,149-151] Neighbouring group participation or alkyl migration may occur after rate determining ionization, in which case no anchimeric assistance can be observed.

For primary and most secondary substrates, k_c is known to be unimportant,[9,37,149-151] so that the observed rate constant for solvolysis, k_t, is given by equation 4.[9] This treatment

$$k_t = k_\Delta + k_s \qquad (4)$$

ignores ion-pair return and the quantity F, the fraction of ion-pairs that proceed to products, is sometimes used, (equation 5). The

---

* Schleyer[149] has argued that "k_c is not regarded as a discrete process, but merely the limit to which k_s and k_Δ tend as assistance vanishes." Raber, Harris and co-workers,[148] however, "find the term (k_c) to be a useful descriptor for those real cases in which solvent assistance is too small to be detected, e.g. 2-adamantyl".

$$k_t = Fk_\Delta + k_s \qquad (5)$$

$$\therefore \quad Fk_\Delta/k_t = 1 - k_s/k_t \qquad (6)$$

quantity $(1-k_s/k_t)\times 100$ represents the percentage of molecules undergoing solvolysis with participation. The term k_s, however, cannot be experimentally determined, but in some cases it may be estimated by comparison with rate constants for the solvolysis of similar substrates for which neighbouring group participation is insignificant.

The rate of solvolytic displacement reactions can be predicted by the use of empirical equations which consider solvent ionizing power (Y) and solvent nucleophilicity (N) as the only solvent parameters.* In the Grunwald-Winstein equation (7), ℓ and m represent, respectively,

$$\log(k/k_o) = \ell N + mY \qquad (7)$$

substrate response to the variation in solvent nucleophilicity and ionizing power, k_o is the rate constant for the substrate solvolysis in 80% aqueous ethanol and k is the rate constant for substrate solvolysis in solvent of nucleophilicity N and ionizing power Y.[147,152] The ionizing power parameter, Y, was introduced by Grunwald and Winstein[147,153] and was defined by equation (8) with m = 1 for *t*-butyl chloride at 25°;

$$\log(k/k_o) = mY \qquad (8)$$

k and k_o have the same meaning as above. More recently, *t*-butyl chloride has been shown to exhibit non limiting behaviour** in solvents of low

---

* This subject had been reviewed recently by Bentley and Schleyer.[147]

** "Limiting" solvolytic behaviour describes solvolyses in which there is no nucleophilic solvent assistance (k_s).[148,149]

nucleophilicity.[147,148,150,151,153-161] As different leaving groups show different variations in solvation with a range of solvents,[147] Schadt, Bentley and Schleyer have introduced a scale of ionizing power for *p*-toluenesulphonate esters, Y_{OTs}, based on 2-adamantyl *p*-toluenesulphonate (Table 1).[151] Values of solvent nucleophilicity (N and N_{OTs}) were first

Solvent	Y_{OTs}	N_{OTs}
Trifluoroacetic acid	4.57	-5.56
Water	4.0	-0.41
97% w/w Hexafluoropropan-2-ol	3.61	-4.27
Formic acid	3.04	-2.35
Trifluoroethanol	1.80	-3.0
Acetic acid	-0.61	-2.35
Ethanol	-1.75	0.0

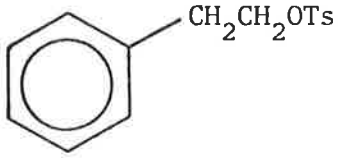
Table 1. Values of solvent ionizing power (Y_{OTs}) and solvent nucleophilicity (N_{OTs}). From references 147 and 151.

evaluated by Bentley, Schadt and Schleyer in 1972 (Table 1);[162] ℓ was defined as unity for methyl *p*-toluenesulphonate.[162]

For primary substrates k_s is favoured by solvents of high nucleophilicity and conversely disfavoured by solvents of low nucleophilicity, whilst k_Δ is largely independent of solvent nucleophilicity.[9,34] Although an increase in solvent ionizing power enhances both k_Δ and k_s, the former is favoured to a greater extent;[34,163] this has been attributed to the greater stabilization of the transition for the k_Δ pathway where

the positive charge is delocalized to a greater extent.[163] That higher solvent ionizing power enhances k_{Δ}, may be illustrated by comparing formic acid with acetic acid; formic acid has a much higher ionizing power than acetic acid, however, both solvents have the same nucleophilicity. The work of Johnson and co-workers[58] concerning 5-hexenyl *p*-nitrobenzenesulphonate (16) is an example; these workers reported that (16) solvolyses in buffered formic acid to give 68% cyclized products, whereas Bartlett and co-workers[60] have reported that (16) solvolyses in buffered acetic acid to give 16.3% cyclized products.

The effect of solvent on the extent of π-bond participation may be best illustrated by the solvolysis of β-phenylalkyl derivatives for which there is a wealth of data.[10,12,15b,34-41,43-52] The extent of π-bond involvement, on the basis of both kinetic and product studies, increases markedly as the solvent is varied through the sequence: ethanol, acetic acid, formic acid and trifluoroacetic acid.[34,37] The rate enhancements for the solvolysis of 2-phenylethyl *p*-toluenesulphonate (45)



(45)

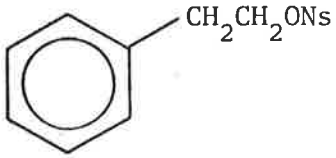
compared to ethyl *p*-toluenesulphonate in ethanol is 0.24; acetic acid, 0.37; formic acid, 2.0; trifluoroacetic acid 3040.[10,38] By means of suitably isotopically labelled 2-phenylethyl derivatives, the observed rate constants have been partitioned between the k_Δ and k_s pathways;[39,44-47] the following k_Δ/k_s ratios (and percentage of aryl participation) have been obtained: ethanol, 0.006; acetic acid, 1.2 (*ca.* 10%); formic acid, 9 (90%); trifluoroacetic acid, 23,000 (100%).[39,44-47] Stereochemical methods[40] and Hammett or Taft correlations[48,49] have also been used and give similar results, i.e. aryl participation in β-arylalkyl derivatives is enhanced for solvents of high ionizing power and low nucleophilicity.[34,37] Schleyer and co-workers[34] have shown that solvent nucleophilicity is the more important factor.

Three solvents of high ionizing power and low nucleophilicity are trifluoroacetic acid, 2,2,2-trifluoroethanol and 1,1,1,3,3,3-hexafluoropropan-2-ol (Table 1).* Although trifluoroacetic acid has been shown to enhance neighbouring group participation,[38,39,41,52,164,165] it suffers from the disadvantage of being highly acidic (pKa-0.23[166]). Trifluoroethanol recently has become a popular solvolysis medium[19,24,34-36,63,68,74,118,148,151,154-160,163,167-186] because of its low nucleophilicity,[26,34,74,151,154,155,167-172] high ionizing ability[34,151,154,155,167,168] and low acidity (pKa 12.4,[188,189] 12.8[190]). It has been demonstrated that neighbouring group participation is enhanced by the use of trifluoroethanol compared to the more usual solvolysis solvents such as ethanol, acetic acid and formic acid;[34-36,63,68,74,118,144,145,163,172-175,187] to date, however, there has

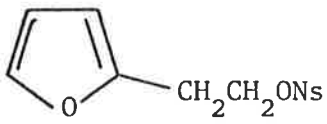
---

* In this thesis 2,2,2-trifluoroethanol and 1,1,1,3,3,3-hexafluoropropan-2-ol will be abbreviated to trifluoroethanol and hexafluoropropan-2-ol, respectively.

been little work reported concerning double bond participation in trifluoroethanol.[63,68,74,144,145,187] Noyce and co-workers[35,36] have shown that 2-phenylethyl *p*-nitrobenzenesulphonate (46) solvolyses in trifluoroethanol 17.5 times faster than ethyl *p*-nitrobenzenesulphonate and suitably isotopically labelled derivatives solvolyse with essentially complete aryl participation. Noyce and Castenson[35] have also examined participation by heterocyclic β-arylalkyl derivatives in trifluoroethanol; the extent of such participation was increased in trifluoroethanol compared to formic



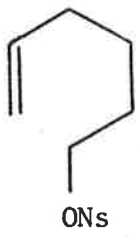
(46)



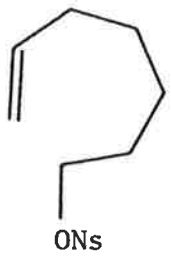
(47)

acid or acetic acid.[35] In addition, 2-(2'-furyl)ethyl *p*-toluenesulphonate (47) did not undergo acid catalysed decomposition in buffered trifluoroethanol whereas this was a problem for formic acid.[35]

Trahanovsky and Doyle[74] have found increased amounts of cyclized products for the solvolysis of 5-hexenyl and 6-heptenyl *p*-nitrobenzenesulphonates [(16) and (48), respectively] in buffered trifluoroethanol compared to buffered formic acid or acetic acid. The 5-hexenyl derivative (16) gave at least 93% cyclized products in buffered trifluoroethanol compared to 16.3% in buffered acetic acid[60] and *ca.*60% in buffered formic

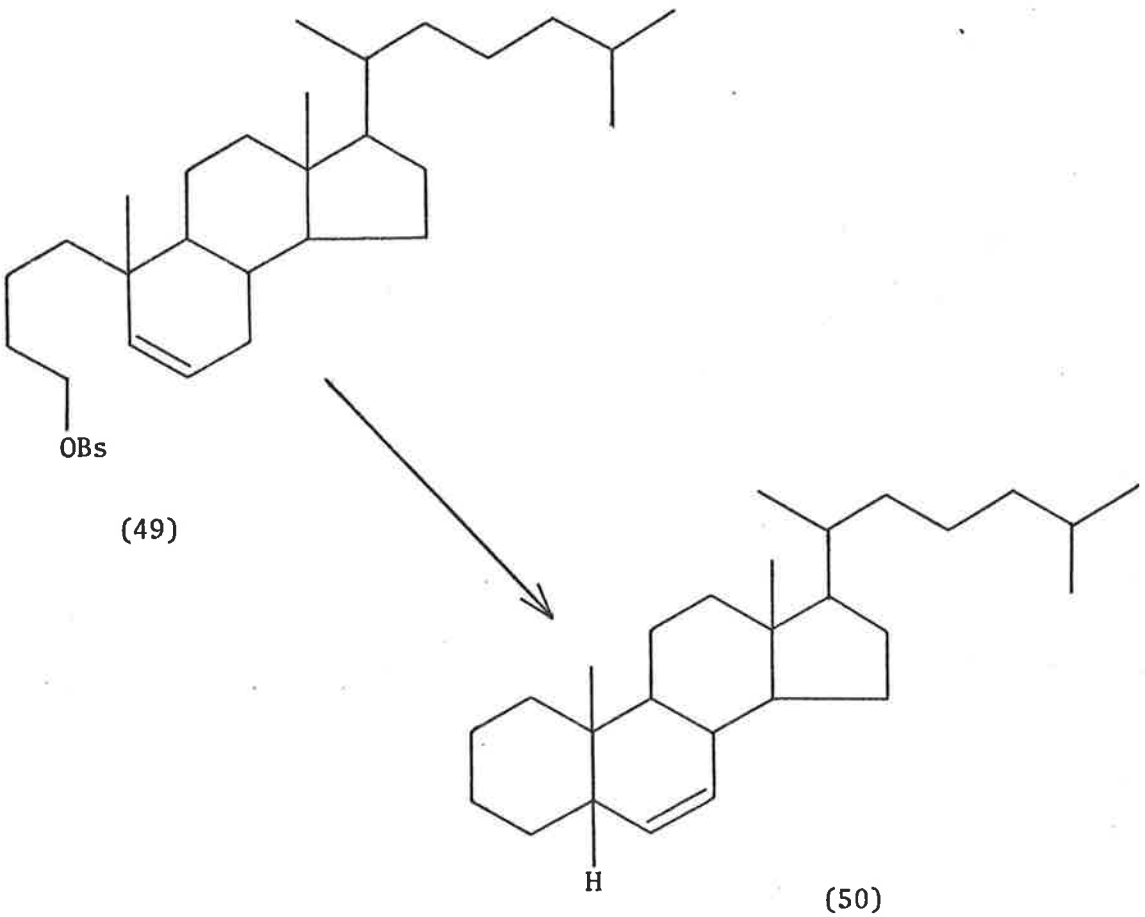


(16)



(48)

acid.[58] The 6-heptenyl derivative (48), which gave no cyclized products in buffered acetic acid and 1% in buffered formic acid gave at least 17% cyclized products in trifluoroethanol.[74]



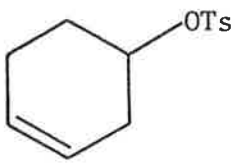
(49)

(50)

Cunningham and Overton[68] solvolysed the *p*-bromobenzenesulphonate (49) in trifluoroethanol and obtained 5-β-cholest-6-ene (50) as one of the products.

Trifluoroethanol also has found use as a solvent for double bond participation in vinylic trifluoromethanesulphonates[63] and in polyolefin cyclizations.[144,145,187]

In 1974, Schadt and Schleyer[168] suggested that hexafluoropropan-2-ol would be a useful solvent for solvolytic studies and synthetic cyclizations because of its low nucleophilicity,[25,151,168,171] high ionizing power[151,168] and moderate acidity (pKa 9.3[190,191]). To date, however, hexafluoropropan-2-ol has found relatively little use as a solvolysis medium.[25,26,151,161,168,171] The only reported example of double bond participation in solvolysis in hexafluoropropan-2-ol is that of homoallylic participation in cyclohex-3-enyl *p*-toluenesulphonate (51). Lambert and Feartherman[25,26] have shown that (51) solvolyses in hexa-



(51)

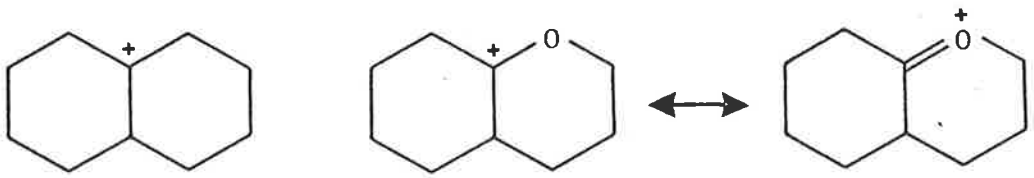
fluoropropan-2-ol exclusively with homoallylic participation to give products with 100% retention of configuration at carbon 1; the use of

acetic acid and formic acid gave 17 and 40% retention, respectively, whilst 70% aqueous 1,4-dioxane gave complete inversion.

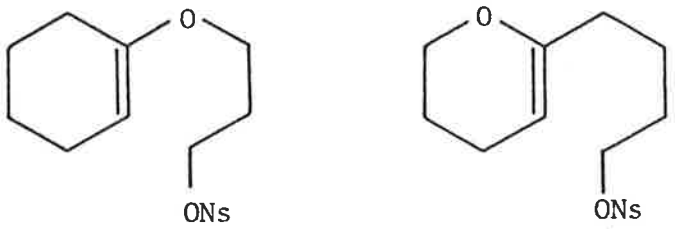
A mixture of heptane and hexafluoropropan-2-ol has been used as a solvent for an acid catalysed polyolefin cyclization.[187]

The objectives of the project described in this thesis

In earlier work in this department,[1] a study of the π-routes to the 9-decalyl cation (52) was undertaken. As an extension of this work, it was decided to study two π-routes to the 1-oxa-9-decalyl ion (53).[192-194] The two routes that were chosen for study were those from 3-(cyclohex-1'-enyloxy)propyl *p*-nitrobenzenesulphonate (54) and 4-(2'-oxacyclohex-1'-



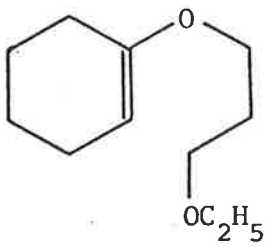
(52) (53)



(54) (55)

enyl)butyl *p*-nitrobenzenesulphonate (55). The ester (54), first synthesized by Stoneman,[192] was expected to solvolyse in acetic acid with a rate enhancement greater than that observed for 4-(cyclohex-1'-enyl)-

butyl *p*-nitrobenzenesulphonate (18); unexpectedly, however, Stoneman found that the ester did not give a large rate enhancement. By means of a nuclear magnetic resonance (n.m.r.) study using deuterated acetic acid, the lack of π-bond participation was shown to be due to the rapid addition of acetic acid to the double bond of the enol ether.[193] In the less acidic solvent, ethanol (buffered with sodium ethoxide), Stoneman[192] found a small rate enhancement for the solvolysis of (54); the only product detected, however, was 3-(cyclohex-1'-enyloxy)propyl ethyl ether (56) (60% yield).

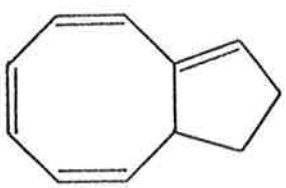


(56)

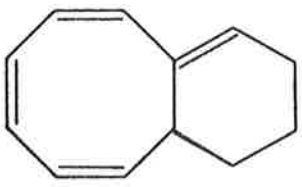
In view of the lack of π-bond participation during the solvolysis of (54) in the nucleophilic solvent, ethanol, it was decided to investigate (by means of kinetic and product studies) the solvolysis of (54) in the less nucleophilic and more ionizing solvent, trifluoroethanol. Product studies for the solvolysis of (54) in ethanol buffered with sodium ethoxide and both kinetic and product studies in ethanol buffered with triethylamine were also undertaken; the results of these studies are reported and discussed in Chapter 1.

The synthesis of the other precursor to the ion (53) i.e. (55) was first reported by McKenzie;[194] in the present work, however, this ester proved to be too labile and the synthesis of more stable derivatives was investigated. The results of these investigations are reported in Chapter 2.

Following the successful use of trifluoroethanol for the generation of the ion (53) *via* the π-route (see Chapter 3), it was decided to investigate the use of this solvent and hexafluoropropan-2-ol for the solvolysis of other substrates that are known to proceed with little π-bond participation in acetic acid. The substrates that were chosen include those with double bonds in the 4,5 position from the leaving group i.e. 3-(cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate (27) (Chapter 3), 4-pentenyl *p*-nitrobenzenesulphonate (26) (Chapter 3) and 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) (Chapter 5). Although 4-phenylbutyl *p*-nitrobenzenesulphonate (23) and 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) have π-bonds in the 5,6 position relative to the leaving group, their solvolysis in acetic acid proceeds only partially *via* the π-route; the solvolyses of (23) and (21) in both trifluoroethanol



(57)



(58)

and hexafluoropropan-2-ol are reported and discussed in Chapters 4 and 6 respectively.

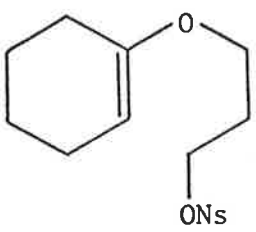
The isolation and characterization of bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57) (Chapter 5), bicyclo[6.4.0]dodeca-2,4,6,8(9)-tetraene (58) (Chapter 6) and their tetracyanoethylene adducts (Chapter 7) is also reported.

CHAPTER 1

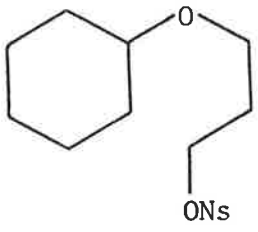
The solvolysis of 3-(cyclohex-1'-enyloxy)propyl *p*-nitrobenzenesulphonate in buffered ethanol and trifluoroethanol

1.1 Synthesis of the required materials

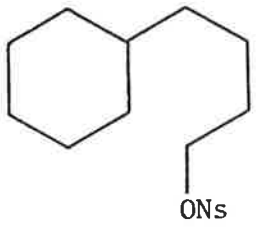
3(cyclohex-1'-enyloxy)propyl,[192] 3-cyclohexyloxypropyl[192] and 4-cyclohexylbutyl *p*-nitrobenzenesulphonates[1] [(54), (59) and (60) respectively] were synthesized by methods that have been described



(54)



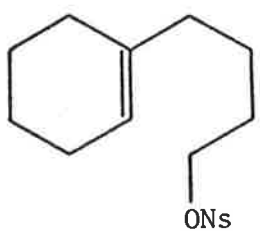
(59)



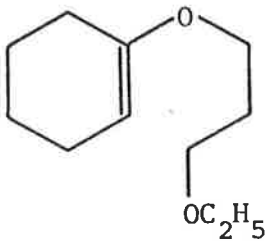
(60)

previously. The ester (54) was found to decompose readily, even when stored in ampoules at -15°; consequently, it was used as soon as possible after its preparation and recrystallization. A sample of 4-(cyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (18) was available from earlier work in this department.[1]

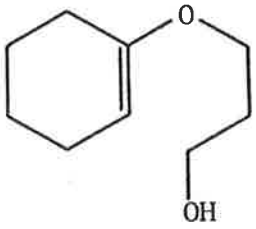
Some of the possible products from the solvolysis of (54) in ethanol or trifluoroethanol were also synthesized; 3-(cyclohex-1'-enyloxy)propyl ethyl ether (56) was prepared by the treatment of the sodium salt of 3-(cyclohex-1'-enyloxy)propanol (61) with ethyl iodide in dimethylformamide.



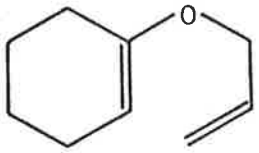
(18)



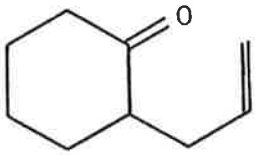
(56)



(61)



(62)



(63)

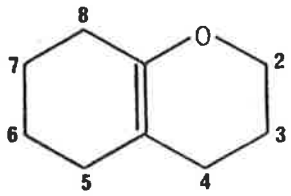
Cyclohex-1-enyl allyl ether (62) was obtained from the acid catalysed elimination of one equivalent of allyl alcohol from cyclohexanone diallyl acetal[195,196] by the method of Lorette and Howard.[197] 2-Allylcyclohexanone (63) was obtained as a by-product; this product is postulated to arise from the Claisen rearrangement of (62).[197,198]

3,4,5,6,7,8-Hexahydro-2H-1-benzopyran (64) was synthesized from 3,4-dihydro-2H-1-benzopyran (65) by the method of Borowitz and co-workers;[199] the dihydrobenzopyran (65) was synthesized from 1,3-diphenoxypropane as described.*[200]

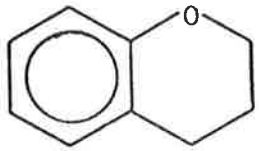
Treatment of a solution of (64) in 'super dry' ethanol with a catalytic amount of p-toluenesulphonic acid gave a mixture (14:86) of 8aα and β-ethoxy-3,4,4aα,5,6,7,8,8a-octahydro-2H-1-benzopyran [(66a)

---

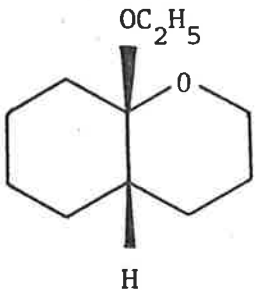
* The two compounds (64) and (65) are also known as 5,6,7,8-tetrahydrochroman and chroman, respectively.



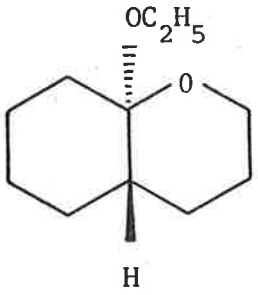
(64)



(65)



(66a)



(66b)

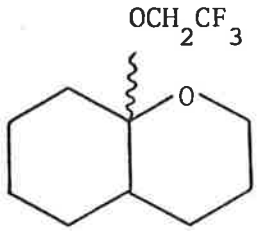
and (66b) respectively]; heating this reaction mixture for an extended period (4 days) did not alter the *cis/trans* isomer ratio. The solvomercuration-demercuration[201] of (64) in the presence of ethanol gave the same two products in the same proportion. Both of the ethers* were found to readily undergo elimination of ethanol to give the enol ether (64); consequently, despite numerous attempts, pure samples of the two ethers could not be obtained (see experimental section). Although a sample of the major isomer that was homogeneous by g.l.c. could be obtained, distillation (short path, temperature 50°) always resulted in some decomposition, and samples that had been stored at -15° in ampoules sealed under nitrogen, for longer than a few days were found, when opened, to have decomposed completely to the enol ether (64).

---

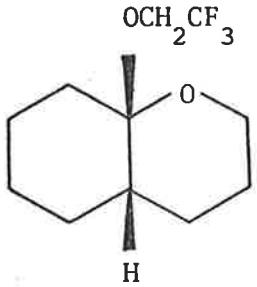
* Interestingly, the major product underwent elimination of ethanol more readily than the minor product.

Examination of models show that there is a greater extent of non-bonded interactions for the *cis* isomer (66a) than for the *trans* isomer (66b) and thus the latter is expected to be the thermodynamically more stable. In view of this, the major product from the acid catalysed addition of ethanol to (64) is tentatively identified as the *trans* isomer (66b) and the minor product as the *cis* isomer (66a).*

The addition of trifluoroethanol to (64) (either acid catalysed or solvomercuration-demercuration) gave only one isomer of the trifluoroethyl ether (67) and starting material (16:84, respectively);



(67)



(67a)

---

* The acid catalysed addition of methanol to the carbon analogue of (64) i.e. 1,2,3,4,5,6,7,8-octahydronapthalene, has been reported to give the *cis* and *trans* isomers (20:80, respectively) of 4a-methoxy-1,2,3,4,4a,5,6,7,8,8a-decahydronapthalene.[202] This would appear to be a good analogy for (66a) and (66b) as the anomeric effect[203-206] would be expected to affect both isomers equally. Dale[207] has discussed the conformational consequences of replacing methylene groups by an ether oxygen. Some French workers[208] have reported the isolation of 8a-methoxy-3,4,4a,5,6,7,8,8a-octahydro-2H-1-benzopyran from the treatment of (64) with hydrogen chloride and methanol; no mention of isomers was made, however.

this 16% conversion was independant of reaction time and method (see experimental section). A possible explanation for this is that both *cis* and *trans* trifluoroethyl ethers are formed (16:84, i.e. similar to that found for the ethyl ethers), but the *trans* isomer might be undergoing elimination of trifluoroethanol during work-up. Accordingly, the product obtained from the acid catalysed addition of trifluoroethanol to (64) is tentatively identified as the *cis* isomer (67a).

1.2 Kinetic results

Rate constants were obtained for the solvolysis of 3-(cyclohex-1'-enyloxy)propyl and 3-cyclohexyloxypropyl *p*-nitrobenzenesulphonates [(54) and (59) respectively] in ethanol buffered with triethylamine (Table 3) and trifluorethanol buffered with triethylamine (Table 4); the results of Stoneman[192] for the solvolysis of (54) and (59) in ethanol buffered with sodium ethoxide are shown in Table 2 along with

Temp. (°C)	10^5k for *p*-nitrobenzenesulphonates (54)[A]	(59)	(60)	k_{unsat}/k_{sat}
32.6	4.1(0.2)[B]			
39.85	7.7(0.1)[B]			
40.2	8.2[E]	5.65(0.25)[B]	11.2(0.3)[C] 11.3(0.4)[D]	1.4
47.5	16.9(0.5)[B]			
69.9	116[E]			

Table 2. Rate constants for the solvolysis of *p*-nitrobenzenesulphonates in ethanol containing sodium ethoxide. The values in brackets are standard deviations. A. Activation parameters, $\Delta H^{\neq}$ 77±6 kJmol^{-1}, $\Delta S^{\neq}$ -77±20 JK^{-1}mol^{-1} were recalculated from the data of Stoneman.[192] B. Data from reference 192; the solutions were initially 0.01M in ester and 0.016M in sodium ethoxide. C. Obtained by the method described in reference 192. D. Obtained spectrophotometrically (experimental section, method A); the solutions were initially 0.0025M in ester and 0.01M in sodium ethoxide. E. Extrapolated.

those obtained for the solvolysis of 4-cyclohexylbutyl *p*-nitrobenzenesulphonate (60). For comparison purposes, the rate constants for the solvolysis of 4-(cyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (18) and its corresponding saturated derivative (60) in buffered trifluoroethanol were also obtained (Table 5).

The observed rate enhancement (k_{unsat}/k_{sat} = 1.4) found by Stoneman[192] for the solvolysis of (54) in ethanol buffered with sodium ethoxide suggests that the extent of π-bond participation is not large. In order to estimate the magnitude of such assistance, the rate of nucleophilic solvent assistance (k_s) for the substrate (54) is required; this may be estimated by assuming that the adverse inductive effect of the enol ether moiety in (54) is similar to that of the ether function of (59) i.e. $k_s = k_{sat}$. If we make this assumption and substitute the appropriate values in equation (4), then k_Δ/k_{unsat} = 0.31 i.e. the extent of cyclization would be 31%; this value is close to that observed (30%, see later).

The rate constants for the solvolysis of (54) and (59) in ethanol buffered with triethylamine (Table 3) were obtained

Temp. (°C)	10^5k for *p*-nitrobenzenesulphonates (54)[A]	(59)	k_{unsat}/k_{sat}
49.4	4.90(0.11) 5.04(0.11)		
60.2	17.3(0.3) 17.6(0.6)		
69.9	40.6(1.5) 41.0(1.8)	10.8(0.2) 10.8(0.2)	3.8

Table 3. Rate constants for the solvolysis of *p*-nitrobenzenesulphonates in ethanol containing triethylamine. The solutions were initially 0.0025M in ester and 0.01M in triethylamine. The values in brackets are standard deviations. A. Activation parameters, $\Delta H^{\neq}$ 93.8±2.2 kJmol^{-1}, $\Delta S^{\neq}$ -37±6 JK^{-1}mol^{-1}.

spectrophotometrically using the ampoule technique (see experimental section, method A); the rate enhancement was found to be 3.8. A similar calculation to that above predicts that the extent of cyclization should be of the order of 73%. The difference between this value and that found experimentally (84%, see later) may, at least in part, be due to the different inductive effects of the oxygen function in the two compounds, (54) and (59).

For the solvolysis of (54) and (18) in buffered trifluoroethanol (Tables 4 and 5, respectively), the rate constants were determined spectrophotometrically (see experimental section, method B);

Temp. (°C)	10^5k for *p*-nitrobenzenesulphonates (54)[A]	(59)[B]	k_{unsat}/k_{sat}
24.8	16.9(0.1) 17.4(0.1)		
30.0	27.2(0.2) 27.6(0.2)		
35.3	43.6(0.3) 44.5(0.4)		
69.9	644[C]	0.680(0.008) 0.721(0.004)	920

Table 4. Rate constants for the solvolysis of (54) and (59) in trifluoroethanol containing triethylamine. The values in brackets are standard deviations. A. The solutions were initially 0.0002M in ester and 0.0008M in triethylamine. Activation parameters $\Delta H^{\neq}$ 65.8±1.9 kJmol^{-1}, $\Delta S^{\neq}$ -96±6 JK^{-1}mol^{-1}. B. The solutions were initially 0.0025M in ester and 0.01M in triethylamine.
C. Extrapolated.

the rate constants for the saturated analogues [i.e. (59) and (60)] were also determined spectrophotometrically (method A). The large rate enhancement for the solvolysis of (54) in buffered trifluorethanol (i.e. 920) gives a predicted extent of cyclization

Temp. (°C)	10^5k for *p*-nitrobenzenesulphonates (18)[A]	(60)[B]	k_{unsat}/k_{sat}
15.4	5.93(0.04) 5.94(0.03)		
28.8	14.8(0.1) 14.9(0.1)		
35.3	37.6(0.4) 38.7(0.5)		
98.4	3720[C]	6.08(0.07) 6.12(0.07)	610

Table 5. Rate constants for the solvolysis of (18) and (60) in trifluoroethanol containing triethylamine. The values in brackets are standard deviations. A. The solutions were initially 0.0002M in ester and 0.0008M in triethylamine. Activation parameters, $\Delta H^{\neq}$ 66.7±0.4 kJmol^{-1}, $\Delta S^{\neq}$ -94.5±1.4 JK^{-1}mol^{-1}. B. The solutions were initially 0.0025M in ester and 0.01M in triethylamine.
C. Extrapolated.

(see above) of 99.9%; this value is essentially the same as that found experimentally (100%).

1.3 Product Studies

The products for the solvolysis of (54) in ethanol buffered with sodium ethoxide, ethanol buffered with triethylamine and trifluoroethanol buffered with triethylamine are reported in Table 6. Qualitative identification was accomplished by comparison of g.l.c. and g.l.c.-mass spectra characteristics with authentic samples; in addition, in earlier work in this department,[192] the ethyl ether (56) was isolated by Stoneman (in 60% yield) from the solvolysis of (54) in ethanol buffered with sodium ethoxide.

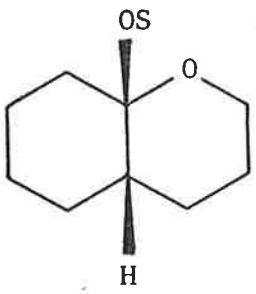
Products	Ethanol/ sodium ethoxide[A,C]	Ethanol/ triethylamine[B,D]	Trifluoroethanol/ triethylamine[A,D]	
(68)[F]	18	51	84	(0)[E]
(69)[F]	12	33	0	(0)
(64)	0	0	16	(100)
(70)	70	16	0	(0)
% cycl.	30	84	100	(100)

Table 6. Relative yields for the solvolysis (after ca. 10 half-lives) of (54). A. ca. 39°. B. 69.9°. C. Solutions were initially 0.01M in ester and 0.016M in sodium ethoxide. D. Solutions were initially 0.01M in ester and 0.02M in triethylamine. E. The figures in brackets are the relative yields of products after a trace of *p*-toluenesulphonic acid had been added to the ethereal solution of products at room temperature for 5 minutes. F. The stereochemistry assigned to these products is tentative.

The *cis* to *trans* ratio of tertiary ethyl ethers formed from the solvolysis in ethanol/sodium ethoxide (60:40, respectively) and ethanol/triethylamine (61:39) is markedly different from that found for the addition of ethanol to tetrahydrochroman (64) (by both acid catalysed addition and solvomercuration-demercuration) i.e. *cis*:*trans*, 14:86, respectively. In order to show that this ratio of ethers obtained *via* solvolysis does not represent the thermodynamic equilibrium, the products from the solvolysis in ethanol buffered with triethylamine were heated under reflux for 16 hr. in 'super dry' ethanol containing a trace of *p*-toluenesulphonic acid; the observed *cis*:*trans* ratio after this treatment was found to be the same as that obtained for the addition of ethanol to tetrahydrochroman (64) i.e. 14:86 respectively. Both tetrahydrochroman (64) and the mixture of tertiary ethyl ethers (66) were quantitatively recovered unchanged when subjected to the conditions of the ethanolyses; the *cis*:*trans* ratio of ethers was also unchanged.

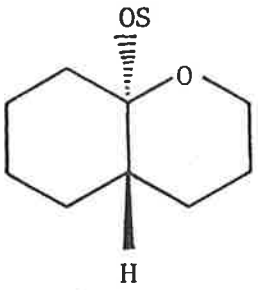
Treatment of the ethereal solution of the products from the solvolysis of (54) in trifluoroethanol with a trace of *p*-toluenesulphonic acid at room temperature for 5 min. resulted in an increased yield of tetrahydrochroman (64); none of the trifluorethyl ether remained after this treatment and no other products were observed.*

No cyclohex-1-enyl allyl ether (62) nor 2-allylcyclohexanone (63) were detected as products from the solvolyses.



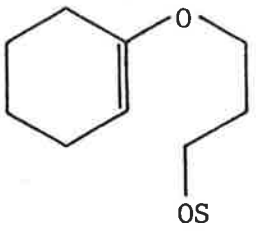
(68)

S = $-CH_2CH_3$ (66a)
or $-CH_2CF_3$ (67a)



(69)

S = $-CH_2CH_3$ (66b)
or $-CH_2CF_3$



(70)

S = $-CH_2CH_3$ (56)
or $-CH_2CF_3$

1.4 Discussion

Both kinetic and product studies (Tables 2-6) show that the solvolysis of (54) in buffered ethanol and trifluoroethanol proceeds, at least in part, by the π-route. The extent of such participation increases dramatically as the solvent is changed from one of high nucleophilicity and low ionizing power [for ethanol, $N_{OTs} = 0.0$, $Y_{OTs} = -1.75$ (see Table 1)] to one of low nucleophilicity and high

---

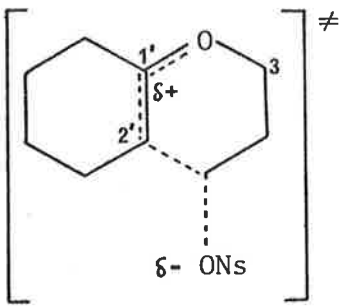
* Despite the fact that many of the reactions giving rise 3,4,5,6,7,8-hexahydro-2H-1-benzopyrans, could also potentially give 3,4,4a,5,6,7-hexahydro-2H-1-benzopyrans, detection of the latter has not been reported.[209-211] Similarly, 2-methylene-3,4,5,6-tetrahydro-2H-pyran has been shown to be destabilized with respect to its double bond isomer 6-methyl-3,4-dihydro-2H-pyran.[212-213]

ionizing ability [for trifluoroethanol, $N_{OTs} = -3.0$, $Y_{OTs} = 1.80$ (see Table 1)]. In ethanol, the increase in the extent of π-bond participation upon changing the buffering agent from sodium ethoxide to the less nucleophilic triethylamine illustrates the effect of the nucleophilicity of the solvent system on the extent of π-bond participation; it is assumed that the small amount of buffering agent present does not significantly alter the ionizing power of the medium.

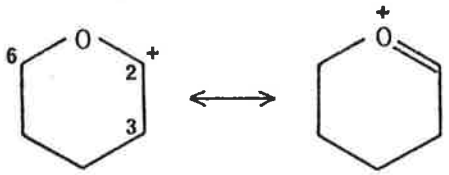
As expected, the rate enhancement for the solvolysis of (54) in buffered trifluoroethanol (i.e. 920) is greater than that of 4-(cyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (18) i.e. 610. This increase, however, is much less than that expected on the basis of (i) the increased nucleophilicity of enol ethers compared to double bonds[75,76,87,88] and (ii) the stabilization of the developing positive charge by delocalization on oxygen[214] in the transition state for the participation by π-bonds of enol ethers. Felkin and Lion[87] have shown that methyl or methoxyl substitution of the double bond of 2-(cyclohex-3'-enyl)ethyl *p*-bromobenzenesulphonate (35) increases the rate of solvolysis in buffered acetonitrile by 6.8 and 97 times respectively; using these values, the enol ether (54) is expected to solvolyse 14 (i.e. 97/6.8) times faster than (18). In buffered trifluoroethanol the observed increase in the solvolysis rate of (54) compared to (18) at both 24.8° and 35.3° is 1.15 i.e. less than one tenth of the enhancement predicted by the above argument.

The reason for this lower rate enhancement than that expected might lie in a decreased extent of delocalization of positive charge on the oxygen atom in the transition state. This argument was first proposed by McKenzie,[194] who stated that orbital overlap between

the p orbitals of the C1'—C2' bond and the orbitals of the lone pairs of electrons on the oxygen atom cannot take place in the transition



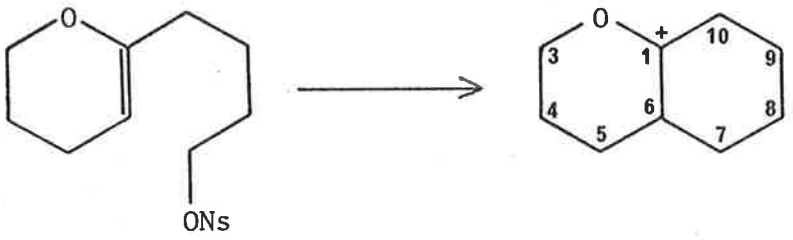
(71)



(72)

state for π-bond participation (71). An alternative approach is to consider the planarity of C1', C2', C3' and the oxygen atom; examination of models show that in order for the carbon bearing the leaving group to closely approach the π-orbitals in the plane of the π-orbitals, C1', C2', C3 and the oxygen cannot be coplanar. It would appear, however, that a coplanar arrangement of these atoms is necessary for maximum delocalization of the developing positive charge. In the case of the ion (72), it has been shown that the extent of such delocalization is maximized by coplanarity of C2, C3, C6 and the oxygen.[205,214]

It should be noted that the solvolysis 4-(2'-oxacyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (55) *via* the π-route would also give the 2-oxabicyclo[4.4.0]dec-1-yl cation (53); in this case, however, there would appear to be no geometric constraints upon the extent of orbital overlap (between the orbitals of the lone pairs of electrons on oxygen and the p orbitals of the double bond) in the

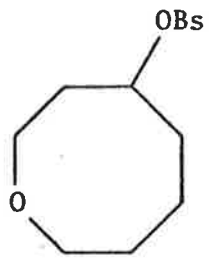


(55) (53)

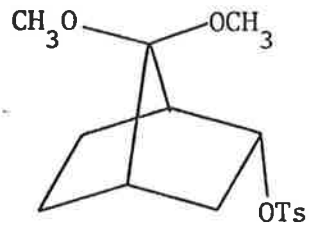
transition state. It was for these reasons that the synthesis of (55) was investigated by McKenzie[194] and in the present work. (Chapter 2).

Consideration of structure (54) shows that a possible competing reaction to π-bond participation is participation by a lone pair of electrons located on the oxygen atom. The participation by oxygen atoms in ethers (and other functional groups) is well documented;[9,16,205] oxygen participation for the structure (54), however, requires the usually unfavourable formation of a 4-membered ring intermediate. Winstein and co-workers[215] have shown that for a series of *w*-methoxyalkyl *p*-bromobenzenesulphonates, the methoxy group provides assistance when a 5 or 6-membered cyclic oxonium ion is possible, but methoxy group assistance is not readily apparent when this intermediate would be a 4-membered ring.[9,215] Paquette and Scott,[216] however, have provided conclusive evidence for oxygen participation in the acetolysis of 4-oxacycloctyl *p*-bromobenzene-sulphonate (73); similarly, Gassman and co-workers[217] have demonstrated

oxygen participation in the solvolysis of the *endo*-ketal (74). These two examples, however, might be regarded as special cases. The

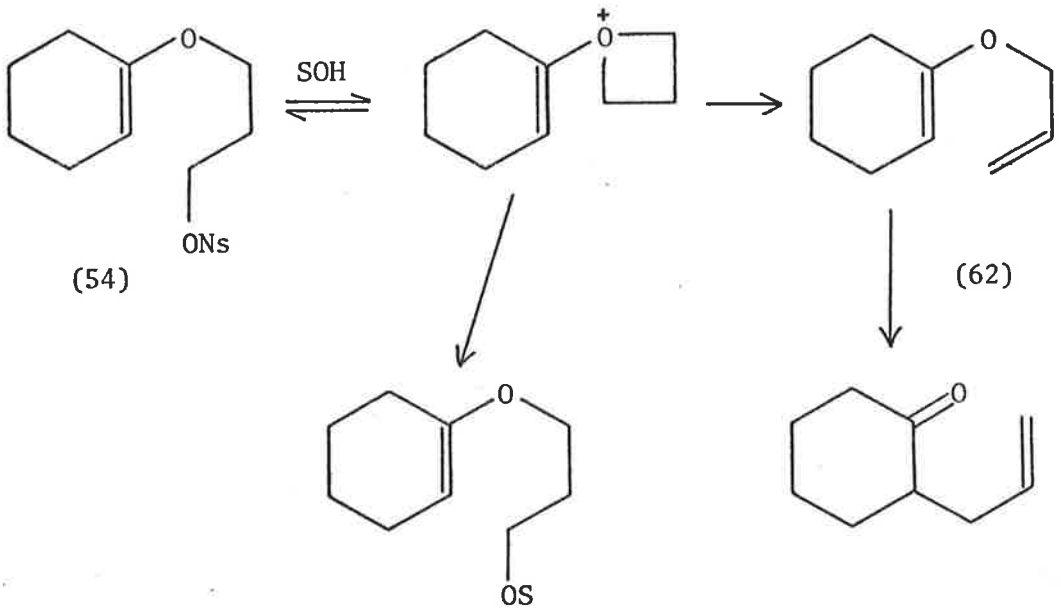


(73)



(74)

products which might result from oxygen participation during the solvolysis of (54) are shown in Scheme 2; as mentioned above,



(54) (62) (70) (63)

Scheme 2

neither (62) nor (63) were detected from the solvolysis of (54) in the solvents studied. In trifluoroethanol, the exclusive formation of products derived from the π-route shows that oxygen participation leading to products does not occur in this solvent. In ethanol, the question of whether the ethyl ether (56) results from oxygen participation or from direct solvolytic displacement of (54) cannot be determined on the evidence available; however, the former mechanism seems unlikely by analogy with the absence of this mechanism in trifluoroethanol.

A further possible competing reaction is direct substitution of (54) by the triethylamine that is used to neutralize the acid liberated by the solvolysis reaction. This process, however, seems most unlikely in view of the very low concentration of triethylamine in comparison to the concentration of solvent. Furthermore, triethylamine (and other Lewis bases) form complexes with trifluoroethanol[218-222] (and hexafluoropropan-2-ol[220-224]); these complexes are the result of hydrogen bonding. The quantitative yield of ether soluble products for the solvolysis of (54) in the solvents studied suggests that displacement by triethylamine to give water soluble triethylalkylammonium salts is not a serious competing reaction.

In summary, the solvolysis of 3-(cyclohex-1'-enyloxy)propyl *p*-nitrobenzenesulphonate (54) in buffered ethanol and trifluoroethanol proceeds partially and completely, respectively, by the π-route; the extent of anchimeric assistance, however, although large, is less than that expected by comparison with that observed for 4-(cyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (18).

The results obtained also show the usefulness of trifluoroethanol for the solvolysis of acid sensitive substrates.*

---

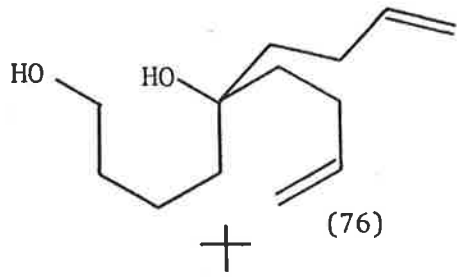
* The ester (54) is unstable in buffered acid.[193] Noyce and co-workers[35] have also demonstrated the usefulness of trifluoroethanol for the solvolysis of acid sensitive substrates.

CHAPTER 2

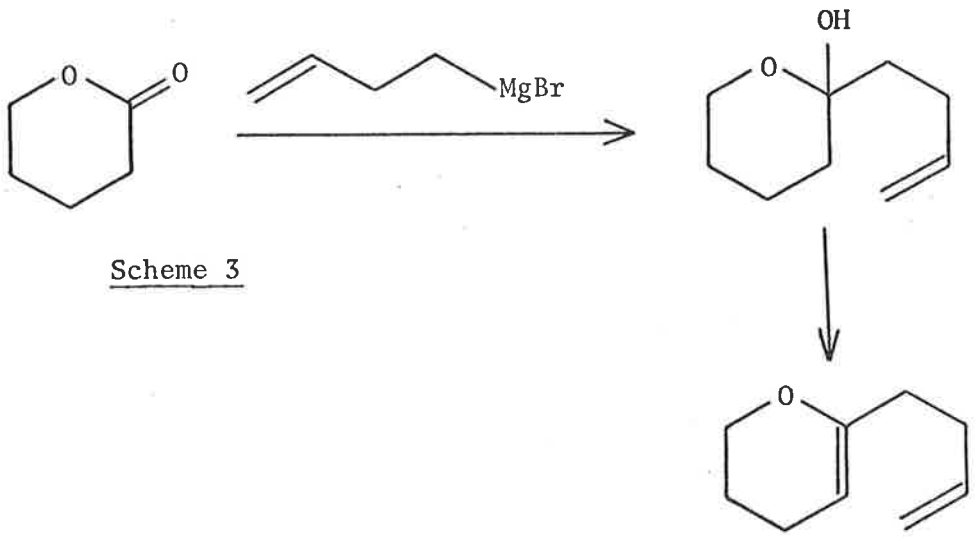
The synthesis of derivatives of 4-(2'-oxacyclohex-1'-enyl)butanol

2.1 Synthesis of 4-(2'-oxacyclohex-1'-enyl)butanol.

4-(2'-Oxacyclohex-1'-enyl)but-1-ene (75) was synthesized as described previously[194,225] (Scheme 3); 5-(but-3'-enyl)non-8-en-1,5-diol (76) was obtained as a by-product. This product presumably arises from the addition of two equivalents of but-4-enylmagnesium bromide to δ-valerolactone. McKenzie[194] has reported the synthesis of



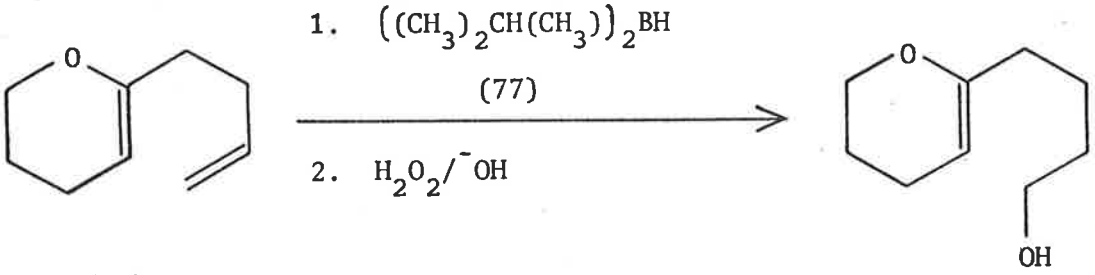
(76)



Scheme 3

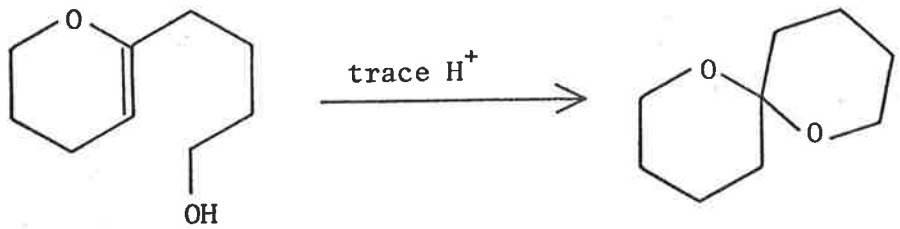
(75)

4-(2'-oxacyclohex-1'-enyl)butanol (78) from (75) using 1.5 equivalents of bis(3-methylbut-2-yl)borane (77). In this earlier work, the 'in situ' method[226] was used for the preparation of the borane;[194] the usual procedure[227] gave only starting material.[194]



(75) (78)

In the present work,* the hydroboration procedure using 1.5 equivalents of borane (77) as described by McKenzie[194] gave only starting material; the use of 4.5 equivalents of borane (77) gave a product which did not possess an enol ether or a double bond. Using 2 equivalents of



(78) (79)

---

* See also reference 193.

borane, and provided that the reaction was carried out on a small scale (2g or less)*, the required alcohol (78) was obtained. The addition of carbon tetrachloride to (78) resulted in the formation of 1,7-dioxaspiro[5.5]-undecane (79); this reaction is presumably catalysed by trace amounts of acid present in the carbon tetrachloride. Accordingly, the alcohol (78) was shown to be stable when diluted with carbon tetrachloride which had been passed through a column of alumina immediately prior to use.

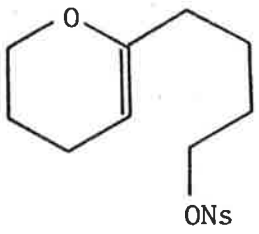
2.2 Attempted preparation of 4-(2'-oxacyclohex-1'-enyl)butyl arenesulphonates

The preparation of a suitable derivative of (78) for solvolysis studies proved to be difficult. McKenzie[194] has reported the isolation of 4-(2'-oxacyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (55) from the treatment of (78) with *p*-nitrobenzenesulphonyl chloride in pyridine. In the present work, however, this procedure gave a crystalline product on only one occasion; all other attempts gave oils that could not be crystallized. On the one occasion that a crystalline solid was obtained, it underwent decomposition when it was added to sodium dried ether in an attempt to recrystallize it. Treatment of (78) with 2-napthalenesulphonyl chloride and an excess of pyridine also gave an oil (see experimental section).

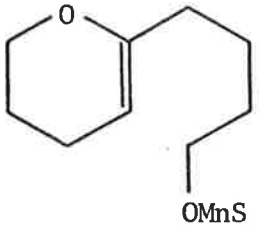
At this stage it was decided to investigate the synthesis of the 6-methylnapthalene-1-sulphonate derivative of (78) i.e. (80);

---

* On one occasion, the hydroboration was carried out on 4.2g of (75). In this case; a mixture (*ca.*1:1) of the required alcohol and an unidentified product (ν_{max} 1725 cm^{-1}) was obtained. Preparative t.l.c. on basic alumina resulted in decomposition; fractional distillation did not give a separation.

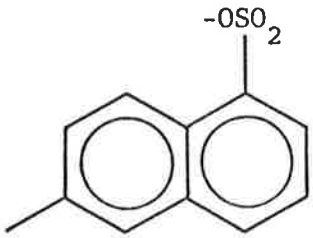


(55)

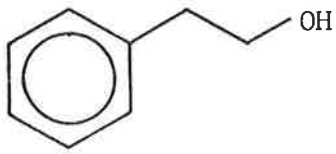


(80)

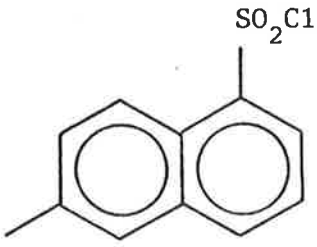
-OMnS =



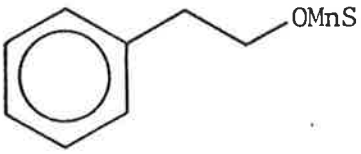
these derivatives have been reported to usually have high melting points, to have similar reactivities as *p*-toluenesulphonates and to facilitate the spectrophotometric determination of solvolytic rate constants.[228] To establish mild conditions for the preparation of these derivatives, 2-phenylethanol (81) was used as a model primary alcohol.



(81)



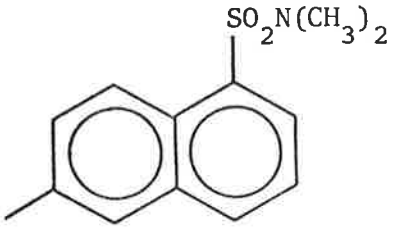
(82)



(83)

Treatment of (81) with 6-methylnapthalene-1-sulphonyl chloride (82)[228] and an excess of pyridine at 0° gave 2-phenylethyl 6-methylnapthalene-1-

sulphonate (83); this sulphonate (83) was also obtained when ether was used as the solvent in the presence of 1.5 equivalents of pyridine. When a solution of potassium 2-phenylethoxide in dimethylformamide was treated with (82) at -15°, 6-methylnapthalene-1-(*N*,*N*-dimethylsulphonamide) (84) was obtained; this structure (84) was confirmed by comparison with



(84)

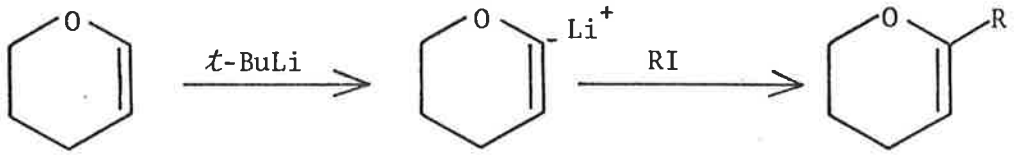
the product obtained from the treatment of the sulphonyl chloride (82) with dimethylamine. This product (84) is thought to arise from the base catalysed decomposition of dimethylformamide[229] to give dimethylamine, which may then react with the sulphonyl chloride (82) to give the observed product. This problem was overcome by adding potassium hydride to a mixture of the sulphonyl chloride (82) and the alcohol (81) in dimethylformamide to give the required sulphonate (83). When 4-(2'-oxacyclohex-1'-enyl)butanol (78) was substituted for 2-phenylethamol (81) in the above procedures, the products obtained did not possess an enol ether function as evidenced by their infrared spectra.

In view of the difficulties encountered in the synthesis of sulphonate derivatives of (78), the synthesis of halides (Section 2.3)

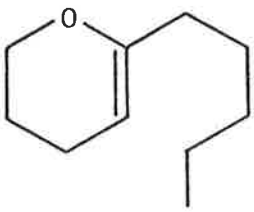
and nitrobenzoates (Section 2.4) were investigated.

2.3 Attempted synthesis of 4-(2'-oxacyclohex-1'-enyl)butyl halides

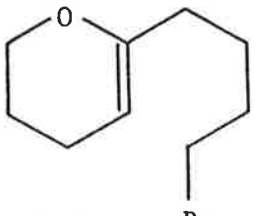
It has been reported that 2-alkyl-5,6-dihydro-4*H*-pyrans (85) may be prepared by the alkylation of the carbanion (86) with alkyl iodides;[230] the carbanion (86) may be prepared by treating dihydropyran with *t*-butyllithium.[230] It was also reported that bromides (and presumably chlorides also) were generally unreactive towards reaction with the carbanion (86).[230] In order to utilize this reaction for



(86) (85)



(87)



(88)

$Cl(CH_2)_4I$ (89)

$Br(CH_2)_4I$ (90)

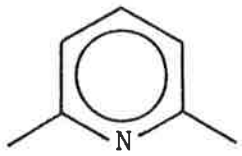
the preparation of 4-(2'-oxacyclohex-1'-enyl)butyl chloride (87) and bromide (88), 1-chloro-4-iodobutane (89) and 1-bromo-4-iodobutane (90) were required. These two dihalides were readily synthesized by treating an excess of 1,4-dichlorobutane and 1,4-dibromobutane, respectively, with sodium iodide in acetone; in both cases the required dihalides could be

readily separated from starting material and 1,4-diodobutane by fractional distillation. Treatment of the carbanion (86) with 1-chloro-4-iodobutane (89) followed by hexamethylphosphoric triamide* gave, after distillation, a fraction whose n.m.r. spectrum suggested that it contained some impurities in addition to the required chloride (87). Attempted purification by preparative g.l.c., preparative t.l.c. or column chromatography on basic alumina resulted in decomposition; distillation through a micro spinning band column did not give a pure sample. Similarly, attempts to prepare the bromide (88) also gave a mixture of the required product and an unidentified product. Attempted purification by fractional distillation was unsuccessful. The bromide underwent decomposition upon column chromatography on basic alumina at room temperature, but no decomposition occurred at 4°C; a pure sample of the bromide could not be obtained, however.

Treatment of alcohols with carbon tetrachloride and triphenylphosphine is known to be a mild method of preparing chlorides.[231] In view of the facile conversion of the alcohol (78) to the spiro compound (79), carbon tetrachloride containing 1% 2,6-dimethylpyridine (91) (2,6-lutidine) was used. Using these conditions, however, the alcohol (78) was converted to the spiro compound (79). When the reaction was repeated using carbon tetrachloride containing 5% 2,6-lutidine, no reaction occurred at room temperature; prolonged heating at 60°, however, again resulted in the

---

* Unexpectedly, reversal of the order of addition of hexamethylphosphoric triamide and the iodide (89) resulted in none of the required product being formed.

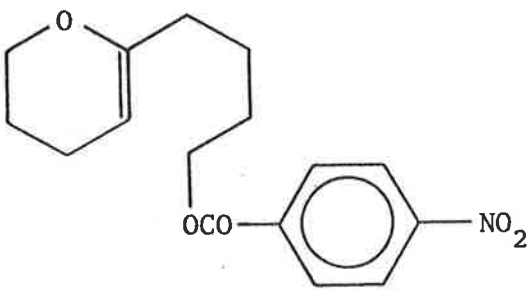


(91)

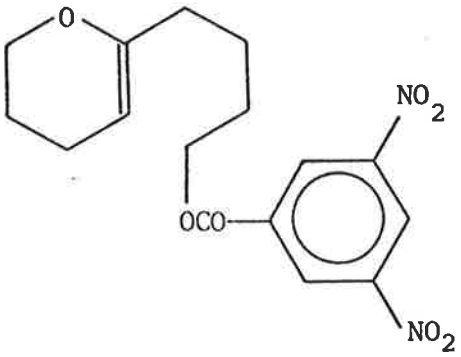
formation of (79). Both the addition of carbon tetrachloride (containing 1% 2,6-lutidine) to a mixture of the alcohol (78) and tri-*n*-butylphosphine and the addition of tri-*n*-butylphosphine to a mixture of the alcohol and carbon tetrachloride (containing 1% 2,6-lutidine) again resulted in the formation of (79).

2.4 Synthesis of nitrobenzoate derivatives of 4-(2'-oxacyclohex-1'-enyl)-butanol

Treatment of potassium 4-(2'-oxacyclohex-1'-enyl)butoxide with *p*-nitrobenzoyl chloride in hexamethylphosphoric triamide at 0° gave an oil whose n.m.r. spectrum was consistent with an impure sample of 4-(2'-oxacyclohex-1'-enyl)butyl *p*-nitrobenzoate (92). Column chromatography on basic alumina gave the spiro compound (79). Difficulties were encountered in obtaining a crystalline sample of (92) and hence the synthesis of the 3,5-dinitrobenzoate derivative (93) was investigated.



(92)



(93)

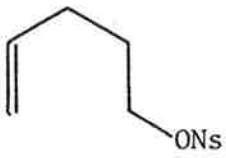
4-(2'-Oxacyclohex-1'-enyl)butyl 3,5-dinitrobenzoate (93) was obtained by two methods: (i) treatment of a solution of the alcohol (78) in tetrahydrofuran with *n*-butyllithium in hexane, followed by the addition of 3,5-dinitrobenzoyl chloride and (ii) treatment of the alcohol (78) with 3,5-dinitrobenzoyl chloride in the presence of pyridine. The ester (93) could be purified by preparative t.l.c. on analytical alumina t.l.c. plates (MERCK).

CHAPTER 3

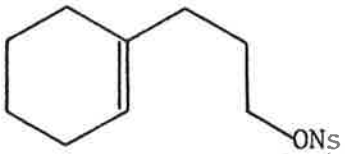
Solvolysis of 3-(cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate in trifluoroethanol and hexafluoropropan-2-ol and the solvolysis of 4-pentenyl *p*-nitrobenzenesulphonate in hexafluoropropan-2-ol

3.1 Synthesis of the required compounds

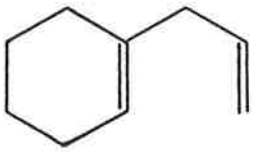
1-Allylcyclohex-1-ene (94), 3-(cyclohex-1'-enyl)propyl and 3-cyclohexylpropyl *p*-nitrobenzenesulphonates [(27) and (95) respectively] were prepared by methods that have been described previously;[2] 4-pentenyl and *n*-pentyl *p*-nitrobenzenesulphonates [(26) and (96) respectively] were prepared from their respective alcohols by the standard procedure.[232]



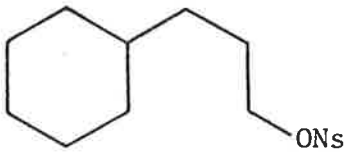
(26)



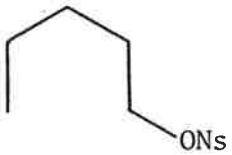
(27)



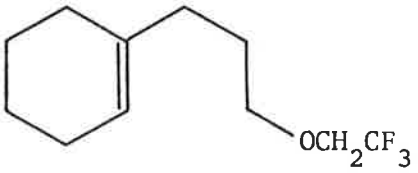
(94)



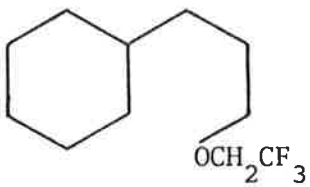
(95)



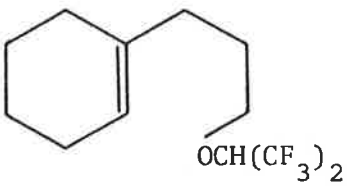
(96)



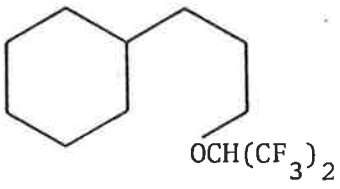
(97)



(98)



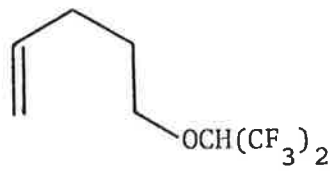
(99)



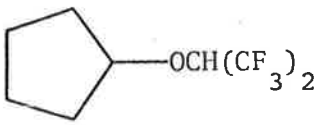
(100)

3-(Cyclohex-1'-enyl)propyl and 3-cyclohexylpropyl 2,2,2-trifluoroethyl ethers [(97) and (98) respectively] were prepared by treatment of their respective sulphonates, (27) and (95), with sodium 2,2,2-trifluoro-

ethoxide in hexamethylphosphoric triamide. 3-(Cyclohex-1'-enyl)propyl and 3-cyclohexylpropyl 1,1,1,3,3,3-hexafluoroprop-2-yl ethers [(99) and (100) respectively] were obtained by preparative solvolyses of the respective sulphonates (27) and (95) in hexafluoropropan-2-ol; in order to facilitate nucleophilic solvent displacement in preference to neighbouring group participation during the preparation of these two ethers, concentrated solutions (0.5M) of the sulphonate in hexafluoropropan-2-ol containing triethylamine (2M) were used. Despite their high molecular weights and high boiling points, these 2,2,2-trifluoroethyl and 1,1,1,3,3,3-hexafluoroprop-2-yl ethers were found to be surprisingly volatile; consequently, special precautions were taken to guard against loss of material during their preparation, purification and handling. Volatility was even more of a problem for 4-pentenyl and cyclopentyl 1,1,1,3,3,3-hexafluoroprop-2-yl ethers [(101) and (102) respectively].



(101)

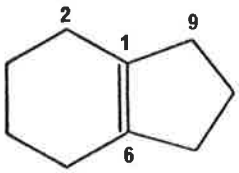


(102)

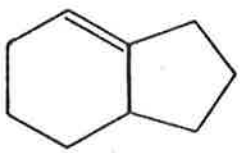
For these two ethers, high boiling solvents were used; the ethers could be separated from solvent by distillation into a receiving flask which was cooled to -78°. After some experimentation, di-*n*-butyl phthalate was found to be a suitable solvent for this purpose. The ether (101) was

prepared by the treatment of the sulphonate (26) with sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide in hexamethylphosphoric triamide. The cyclopentyl ether (102) was prepared by solvomercuration-demercuration[201] of cyclopentene with mercuric trifluoroacetate in the presence of sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide in hexafluoropropan-2-ol; no reaction was observed in the absence of the sodium salt of hexafluoropropan-2-ol.

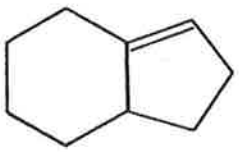
In order to identify the cyclized products from the solvolysis of (27), the 3 olefins: bicyclo[4.3.0]non-1(6)-ene (103), bicyclo[4.3.0]non-1(2)-ene (104) and bicyclo[4.3.0]non-1(9)-ene (105) were required. A



(103)

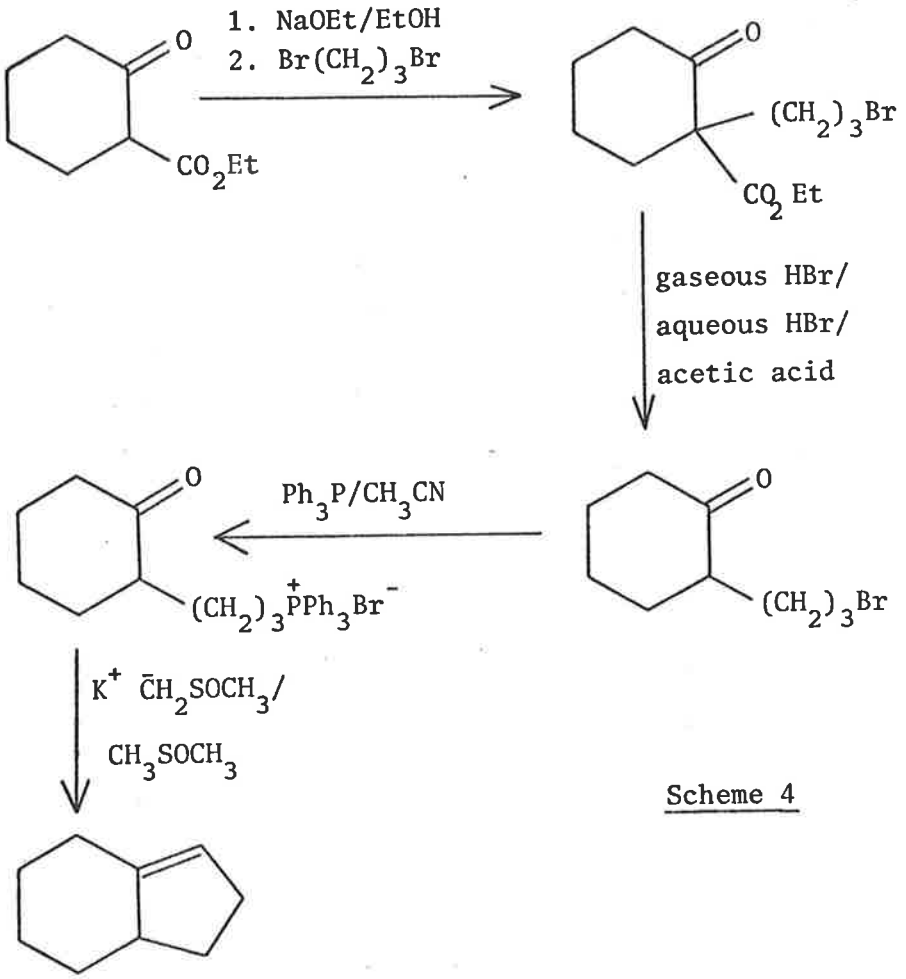


(104)



(105)

pure sample of (103) and a mixture of all three, (103), (104) and (105), were available from earlier work in this department.[2] In order to distinguish between the two trisubstituted olefins, (104) and (105), an unambiguous synthesis of (105) by the method of Grob and co-workers[59] was undertaken (Scheme 4); some modifications to the reported experimental procedures were made, however.



Scheme 4

(105)

1,4 Pentadiene (106) was prepared by pyrolysis of 1,5-pentanediol diacetate as described.[233]

(106)

3.2 Kinetic studies

The rate constants for the solvolysis of 3-(cyclohex-1'-enyl)propyl and 3-cyclohexylpropyl *p*-nitrobenzenesulphonates [(27) and (95) respectively] in buffered trifluoroethanol and buffered hexafluoropropan-2-ol (Table 7) and 4-pentenyl and *n*-pentyl *p*-nitrobenzenesulphonates [(26) and 96) respectively] in buffered hexafluoropropan-2-ol (Table 8) were determined spectrophotometrically by the ampoule technique (see experimental section, method A). The data reported[2,60] for the solvolysis of these substrates in buffered acetic acid are shown for comparison.

p-Nitrobenzene-sulphonate	10^5k Buffered acetic acid[A] (100.0°)	Buffered trifluoroethanol[B] (98.4°)	Buffered hexafluoropropan-2-ol[B] (98.4°)
(27)	6.95	5.99(0.05)	12.09(0.14)
	6.99	6.17(0.05)	12.09(0.14)
(95)	7.96	6.64(0.11)	3.07(0.08)
	8.04	6.86(0.08)	3.21(0.04)
k_{unsat}/k_{sat}	0.87	0.90	3.85

Table 7 Rate constants for the solvolysis of (27) and (95) in the solvents indicated. The values in brackets are standard deviations. A. Data reported in reference 2. The solutions were initially 0.01M in ester and 0.02M in sodium acetate. B. The solutions were initially 0.0025M in ester and 0.01M in triethylamine.

The kinetic data in Tables 7 and 8 suggest that the solvolysis of (27) in hexafluoropropan-2-ol proceeds to a large extent *via* the π-route; the rate constants for the solvolysis of (27) in trifluoroethanol and for

(26) in hexafluoropropan-2-ol, however, suggest that in these cases the extent of π-bond participation is not large.*

p-Nitrobenzene-sulphonate	$10^5 k$ Buffered acetic acid[A] (79.5°)	Buffered hexafluoropropan-2-ol[B] (98.4°)
4-pentenyl (26)	1.03 1.07	0.69(0.02) 0.71(0.02)
n-pentyl (96)		1.87(0.03) 1.87(0.03)
n-hexyl	1.43 1.58	
k_{unsat}/k_{sat}	0.70[C]	0.37

Table 8. Rate constants for the solvolysis of (26), (96) and *n*-hexyl *p*-nitrobenzenesulphonate in the solvents indicated. The values in brackets are standard deviations. A. Data of Barlett and Closson reported in reference 60. The solutions were initially 0.02M in ester and 0.0355M in sodium acetate. B. The solutions were initially 0.0025M in ester and 0.01M in triethylamine. C. The rate of solvolysis of (96) in buffered acetic acid is assumed to be the same as that for *n*-hexyl *p*-nitrobenzenesulphonate.

In order to estimate the extent of π-bond participation by means of equation (4), it is necessary to estimate k_s. The usual approach is to

$$k_t = k_\Delta + k_s \qquad (4)$$

* This treatment assumes that π-bond participation occurs during the rate determining step.

relate k_s to k_{sat} by estimating the effect of the adverse inductive effect of the double bond on k_s. For the solvolysis of (27) in buffered acetic acid, for which no neighbouring group participation is observed, $k_s = 0.87\ k_{sat}$. In trifluoroethanol and more so in hexafluoropropan-2-ol the rate of direct nucleophilic solvolytic displacement (k_s) will be more sensitive to the adverse inductive effect of the double bond than in acetic acid.[52,234] That this is so (for hexafluoropropan-2-ol at least) can be seen by comparing the rate retardations for the solvolysis of (26) compared to its analogous saturated derivative (96) in buffered acetic acid and buffered hexafluoropropan-2-ol (Table 8). Assuming that neighbouring group participation is insignificant for the solvolysis of both (26) and (96) in these two solvents, then the larger rate retardation in hexafluoropropan-2-ol ($k_{unsat}/k_{sat} = 0.37$) compared to that for acetic acid ($k_{unsat}/k_{sat} = 0.7$) may be attributed to the greater sensitivity of k_s in the former solvent to the adverse inductive effect of the double bond.[52,234]

If the factor 0.37 is corrected for the extra alkyl substituents present on the double bond in (27), and this factor, i.e. 0.46 (0.37 x 0.87/0.70), is used as an estimate of the adverse inductive effect of the double bond upon k_s for the solvolysis of (27) in hexafluoropropan-2-ol, then the extent of cyclization is predicted to be 88%. That this is less than that found experimentally (96%, see later) might be due, at least in part, to neighbouring carbon and/or hydrogen participation during the solvolysis of (26) and/or (95). It was found that the solvolysis of (95) in buffered hexafluoropropan-2-ol gave 3 unidentified products (62%) in addition to the expected product i.e. 3-cyclohexylpropyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (100) (38% yield). If we assume that the unidentified products arise from neighbouring carbon and/or hydrogen participation (k_Δ), then for the

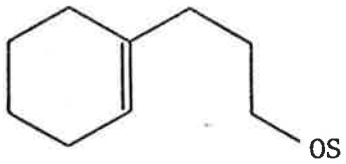
solvolysis of (95) in hexafluoropropan-2-ol, the observed rate constant, k_{sat} is equal to the sum of k_{Δ} and k_s. Assuming that k_{Δ} and k_s are proportional to the yields of products formed from each pathway, then $k_s = (38/100) \times k_{sat}$. Evaluating this expression gives $k_s = 1.19 \times 10^{-5} s^{-1}$ at 98.4°C. Allowing for the adverse inductive effect of the double bond in (27) gives $k_s = 0.547 \times 10^{-5} s.^{-1}$ Using this value as an estimate for k_s for (27), the predicted extent of cyclization for the solvolysis of (27) in hexafluoropropan-2-ol is calculated to be 95.5%. That this value is close to that found experimentally (96%) may well be fortuitous in view of the number of approximations and assumptions used in the calculation. Nevertheless, the closeness of these two values does suggest that the 3 unidentified products from the solvolysis of (95) in hexafluoropropan-2-ol might be the result of neighbouring carbon and/or hydrogen participation.

3.3 Product Studies

The products from the solvolysis of 3-(cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate (27) in buffered trifluoroethanol, buffered hexafluoropropan-2-ol and unbuffered hexafluoropropan-2-ol are reported in Table 9; the products from the acetolysis of (27) are shown for comparison.

The percentage of cyclized products increases in the sequence: buffered acetic acid (0%), buffered trifluoroethanol (30%), buffered hexafluoropropan-2-ol (96%). The cyclized products that were observed for the solvolysis of (27) in these solvents were (103) and (105); surprisingly, none of the olefin (104) was detected. Solvolysis of (27) in unbuffered hexafluoropropan-2-ol gave a slightly greater percentage of cyclization; the increased percentage for the tetrasubstituted olefin (103)

and the detection of a small amount of (104) suggest that some equilibration of the olefins is taking place under these conditions.



(107)

S =-$COCH_3$

or $-CH_2CF_3$ (97)

or $-CH(CF_3)_2$ (99)

Products	% Buffered acetic acid[A]	% Buffered trifluoroethanol[B]	Hexafluoropropan-2-ol buffered[B]	Hexafluoropropan-2-ol unbuffered[C]
(107)	100	70	3	1
(94)	0	0	1	1
(103)	0	18	67	90
(105)	0	12	29	7
(104)	0	0	0	1
% cyclized	0	30	96	98

Table 9 Relative yields from the solvolysis of (27) at 98.4-100° for *ca.* 10 half lives. A. Data reported in reference 2; the solutions were initially 0.01M in ester and 0.02M in sodium acetate. B. The solutions were initially 0.01M in ester and 0.02M in triethylamine. C. The solutions were initially 0.01M in ester.

The products from the solvolysis of 4-pentenyl *p*-nitrobenzenesulphonate (26) in buffered hexafluoropropan-2-ol were found to be: 4-pentenyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (101) (55% absolute yield), 1,4-pentadiene (106) (trace), cyclopentene (1.5%) and an unidentified product (5%); no cyclopentyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (102) was detected. The low recovery is thought to be due to polymerization; the formation of tarry material was observed. The formation of at least 1.5% cyclized products from the solvolysis of (26) in buffered hexafluoropropan-2-ol is greater than that reported[2] for its acetolysis (i.e. 0%).

3-Cyclohexylpropyl 2,2,2-trifluoroethyl ether (98) was the only product detected from the solvolysis of the saturated derivative (95) in buffered trifluoroethanol. As mentioned in section 3.2, the solvolysis of the saturated ester (95) in buffered hexafluoropropan-2-ol, however, gave 3 unidentified products (62% yield) in addition to a 38% yield of the expected product, 3-cyclohexyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (100).

3.4 Discussion

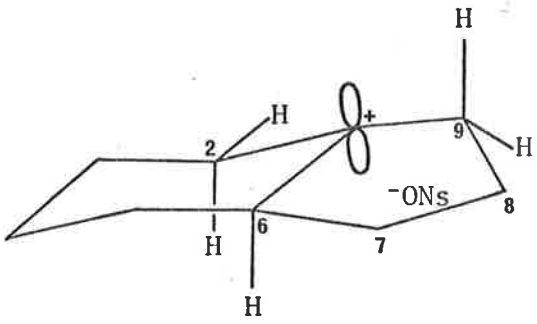
In contrast to the lack of π-bond participation during the acetolysis of (27), both kinetic (Tables 7 and 8) and product studies (Table 9) show that the π-route is important for the solvolysis of (27) in hexafluoropropan-2-ol and to a lesser extent, trifluoroethanol. This result is even more significant when it is remembered that π-bonds in the 4,5-position from the leaving group participate only with difficulty (see Introduction).*

---

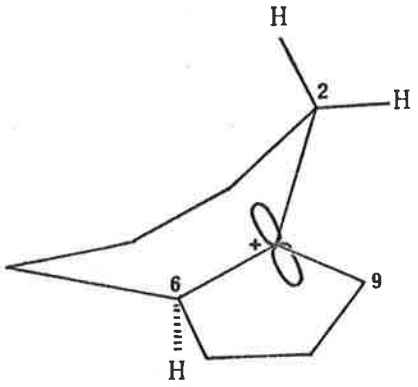
* According to Baldwin's rules for ring closure,[235,236] this cyclization (5-*Endo*-*Trig*) is classified as "disfavoured".

The increased extent of π-bond participation for solvolysis in trifluoroethanol and hexafluoropropan-2-ol has been attributed to the low nucleophilicity and high solvent ionizing power of these solvents.[168] The low solvent nucleophilicity serves to increase the free energy of activation for the competitive direct solvolytic displacement, whilst high solvent ionizing power causes a greater lowering of the free energy of activation for cyclization than for the free energy of activation for direct solvolytic displacement. For the 4-pentenyl system, it would seem that these two factors are insufficient to counter-act the combined effect of (i) the low nucleophilicity of a monosubstituted double bond, (ii) the higher energy of activation that is required for the formation of positive charge on a secondary carbon atom (compared to a tertiary carbon) and (iii) the strain energy that is involved in the formation of the transition state for participation by double bonds located in the 4,5-position from the leaving group.

In earlier work in this department, it has been argued that counter-ions in ion-pairs are involved in product formation.[1,2,53,93,115-117] Gream and co-workers[2] have used this argument to rationalize the formation of (105) from the acetolysis of 4-(cyclopent-1'-enyl)butyl *p*-nitrobenzenesulphonate; the formation of the tetrasubstituted olefin (103), however, could not be explained by the counter-ion in the initially formed ion-pair acting as a base.[2] A similar situation exists for the solvolysis of (27) in buffered trifluoroethanol and buffered hexafluoropropan-2-ol. The solvolysis of (27) *via* the π-route would be expected to give initially the ion-pair (108), where the counter-ion is in the vicinity of the C7-C8 bond and on the opposite side of the molecule to the hydrogen atom at C6. The counter-ion only has to move a short distance to abstract a proton from C9; in order to abstract a proton from C2, however, the



(108)



(108a)

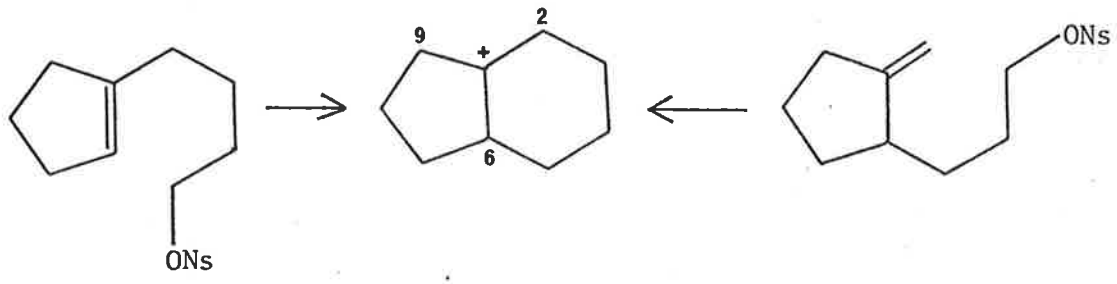
counter-ion would have to move a considerable distance. Furthermore, models show that the hydrogen at C9 on the same side of molecule as the counter-ion can easily adopt a pseudo-axial arrangement.* The hydrogen at C2 on the same side of the molecule as the counter-ion, however, can only adopt an axial configuration if the 6-membered ring exists in a boat conformation (108a). The formation of the tetra-substituted olefin (103) from the ion-pair (108), however, would require the counter-ion to move to the opposite side of the molecule; it would thus seem more likely that a base other than the counter-ion is involved in the formation of the tetra-substituted olefin (103).

One surprising fact concerning the products from the solvolysis of (27) in trifluoroethanol and hexafluoropropan-2-ol is the absence of the olefin (104). Although the above argument favours the formation of (105)

---

* "The possibility of olefin formation is considered only when the C-H bond being broken is coplanar, or almost coplanar, with the vacant p-orbital at the cationic site."[2]

in preference to (104), the complete absence of the latter is difficult to explain. Interestingly, other π-routes to the bicyclo[4.3.0]non-1-yl cation (109) [i.e. from 4-(cyclopent-1'-enyl)propyl and 3-(2'-methylene-cyclopentyl)propyl *p*-nitrobenzenesulphonates, (110) and (111) respectively] also do not give rise to the olefin (104).[2]



(110) (109) (111)

In summary, 3-(cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate (27) solvolyses in buffered trifluoroethanol and hexafluoropropan-2-ol with 30% and 96% π-bond participation, respectively; π-bond participation in this system has not been reported previously.

CHAPTER 4

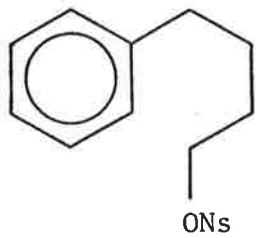
The solvolysis of 4-phenylbutyl *p*-nitrobenzenesulphonate in trifluoroethanol and hexafluoropropan-2-ol

4.1 Synthesis of the required compounds

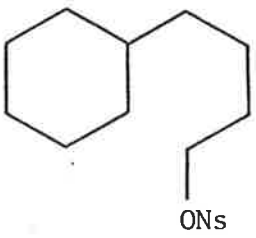
4-Phenylbutyl *p*-nitrobenzenesulphonate (23)[53] and its corresponding saturated derivative, 4-cyclohexylbutyl *p*-nitrobenzenesulphonate (60)[1] were synthesized as previously described.

4-Phenylbut-1-ene (112) was prepared from the treatment of benzylmagnesium chloride with allyl bromide.[237]

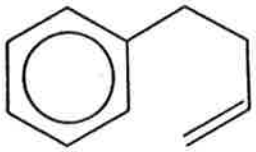
4-Phenylbutyl 2,2,2-trifluoroethyl ether (113) was prepared by the treatment of the ester (23) with sodium 2,2,2-trifluoroethoxide in trifluoroethanol and hexamethylphosphoric triamide. An analogous procedure using sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide in hexafluoropropan-2-ol and hexamethylphosphoric triamide gave 4-phenylbutyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (114).



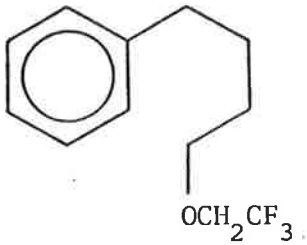
(23)



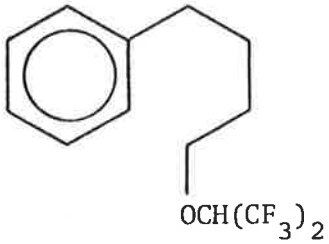
(60)



(112)



(113)



(114)

4.2 Kinetic studies

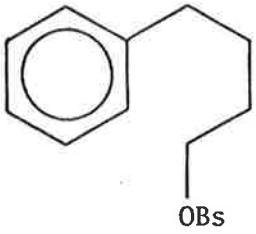
The rate constants for the solvolysis of (23) and (60) in buffered trifluoroethanol (Table 10) and hexafluoropropan-2-ol (Table 11) were obtained spectrophotometrically by the ampoule technique (see experimental section, method A).

The rate enhancements for the solvolysis of (23) in buffered trifluoroethanol (k_{unsat}/k_{sat} = 1.96) and buffered hexafluoropropan-2-ol (k_{unsat}/k_{sat} = 21.4) suggest that (23) solvolyses with extensive π-bond participation in these two solvents. This result is in contrast to the

p-Nitrobenzenesulphonate	T (°C)	$10^5 k$ (s^{-1})	$\frac{k_{unsat}}{k_{sat}}$
4-phenylbutyl (23)[A]	70.4	1.23(0.03) 1.26(0.03)	
	75.0	1.95(0.04) 1.95(0.04)	
	98.4	11.8(0.4) 12.1(0.1)	1.96
4-cyclohexylbutyl (60)	98.4	6.08(0.07) 6.12(0.08)	

Table 10. Rate constants for the solvolysis of (23) and (60) in trifluoroethanol. The solutions were initially 0.0025M in ester and 0.01M in triethylamine. The values in brackets are standard deviations. A. Activation parameters, $\Delta H^{\neq}$ 82.1±0.9 kJmol^{-1} $\Delta S^{\neq}$ -101±3 JK^{-1}mol.$^{-1}$

acetolysis and formolysis results of Winstein and Heck;[109] these workers reported that 4-phenylbutyl *p*-bromobenzenesulphonate (24) solvolyses in acetic and formic acids at 0.98 and 0.96 times, respectively, the rate of solvolysis of *n*-butyl *p*-bromobenzenesulphonate (115) in the same solvent.



(24)

$CH_3(CH_2)_4OBs$

(115)

Furthermore, Gream and Mular[53] have reported that (23) solvolyses in buffered acetic acid with a rate constant of 6.99×10^{-5} s^{-1} at 100° (average of 2 determinations); this value represents a rate enhancement of 0.84 when compared to the rate constant reported[1] for the solvolysis of (60) in buffered acetic acid at 100° [i.e. 8.34×10^{-5} s^{-1} (average of two determinations)].

Bearing in mind the fact that very little π-bond participation would be expected for the solvolysis of (23) in buffered acetic acid*, the above rate retardation ($k_{unsat}/k_{sat} = 0.84$) is an estimate of the effect of the adverse inductive effect of the aryl ring on k_s for (23) compared

---

* Only 5.5% of tetralin is formed from the solvolysis of (24) in acetic acid;[109] in buffered acetic acid, however, cyclization is expected to be even less favourable due to the increased rate of direct solvolytic displacement caused by the added buffering agent.

p-Nitrobenzenesulphonate	T (°C)	10^5k (s^{-1})	$\frac{k_{unsat}}{k_{sat}}$
4-phenylbutyl (23)[A]	64.3	4.62(0.04) 4.65(0.04)	
	70.4	6.96(0.17) 7.07(0.09)	
	75.0	10.7(0.1) 10.8(0.1)	
	98.4	55.9[B]	21.4
4-cyclohexylbutyl (60)	98.4	2.59(0.06) 2.63(0.04)	

Table 11. Rate constants for the solvolysis of (23) and (60) in hexafluoropropan-2-ol. The solutions were initially 0.0025M in ester and 0.01M in triethylamine. The values in brackets are standard deviations. A. Activation paremeters $\Delta H^{\neq}$ 73.7±3.0 kJmol^{-1}, $\Delta S^{\neq}$ -111±9 JK^{-1}mol.$^{-1}$ B. Extrapolated.

to (60) in buffered acetic acid. Using equation (4) and $k_s = 0.84k_{sat}$ for

$$k_t = k_s + k_\Delta \qquad (4)$$

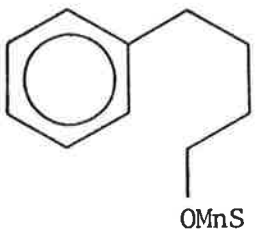
the solvolysis of (23) in buffered trifluoroethanol and hexafluoropropan-2-ol, the extent of cyclization (k_Δ/k_t) is calculated to be 57 and 96%, respectively. These values (i.e. 57 and 96%) are lower than those found experimentally i.e. 69 and 99.5%, respectively (see later); this discrepancy may be attributed to the greater sensitivity to inductive effects for solvolyses in trifluoroethanol and hexafluoropropan-2-ol.[52,234]

4.3 Product studies

The products (after *ca.* 10 half-lives) from the solvolysis of (23) in buffered trifluoroethanol consisted of tetralin (69%) and the trifluoroethyl ether (113) (31%); no 4-phenylbut-1-ene (112) was detected. The solvolysis of (23) in buffered hexafluoropropan-2-ol gave tetralin (99.5%), the hexafluoroprop-2-yl ether (114) (0.5%) and 4-phenylbut-1-ene (112) (trace). When the ether (114) was subjected to the conditions of the solvolysis, a small yield (1.8%) of 4-phenylbut-1-ene was observed; the remaining material was unchanged ether (114) (98.2% yield).

4.4 Discussion

A comparison of the rate enhancements and percentages of cyclization for the solvolysis of 4-phenylbutyl derivatives in various solvents is shown in Table 12. In hexafluoropropan-2-ol and to a lesser extent



(116)

$CH_3(CH_2)_3OMnS$

(117)

trifluoroethanol, the extent of π-bond participation is, as expected, much greater than that reported for the more usual solvolysis solvents such as acetic and formic acids.

Solvent	unsat. ester	sat. ester	T (°C)	$\frac{k_{unsat}}{k_{sat}}$	% cycl.	References
Buffered acetic acid	(23)	(60)	100.0	0.84		1,53
Acetic acid	(24)	(115)	75.0	0.98	5.5	109
Buffered formic acid	(24)	(115)	75.0		19.0	109
Formic acid	(24)	(115)	75.0	0.96		109
Buffered trifluoroethanol	(23)	(60)	98.4	1.96	69.0	
Buffered hexafluoro-propan-2-ol	(23)	(60)	98.4	21.4	99.5	
Buffered trifluoroacetic acid	(116)	(117)	100.0	26.2	100.0	52

Table 12 Rate enhancements and percentages of tetralin formation for the solvolyses of 4-phenylbutyl derivatives in various solvents.

After the present work had been completed, Ando and co-workers[52] reported that the solvolysis of 4-phenylbutyl 6-methylnapthalene-1-sulphonate (116) in buffered trifluoroacetic acid proceeds 26.2 times faster than *n*-butyl 6-methylnapthalene-1-sulphonate (117); the yield of tetralin was 100%.[52] In view of the higher solvent ionizing power and lower nucleophilicity of trifluoroacetic acid compared to hexafluoropropan-2-ol (see Table 1, p.23), the slightly greater rate enhancement in the former solvent is not unexpected.

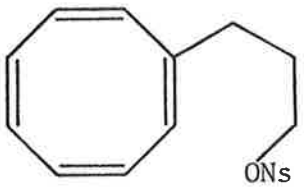
In summary, the usefulness of trifluoroethanol and hexafluoro-propan-2-ol for inducing the cyclization of 4-phenylbutyl derivatives *via* the π-route has been demonstrated; the yield of tetralin formed in these two solvents is 69 and 99.5%, respectively.

CHAPTER 5

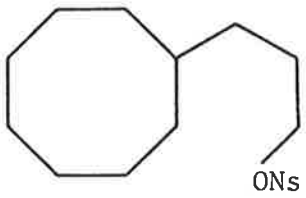
The solvolysis of 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate in trifluoroethanol and hexafluoropropan-2-ol

5.1 Synthesis of the required materials

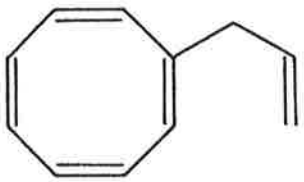
3-Cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29), 3-cyclooctylpropyl *p*-nitrobenzenesulphonate (118) and allylcyclooctatetraene (119) were synthesized as previously described.[53]



(29)

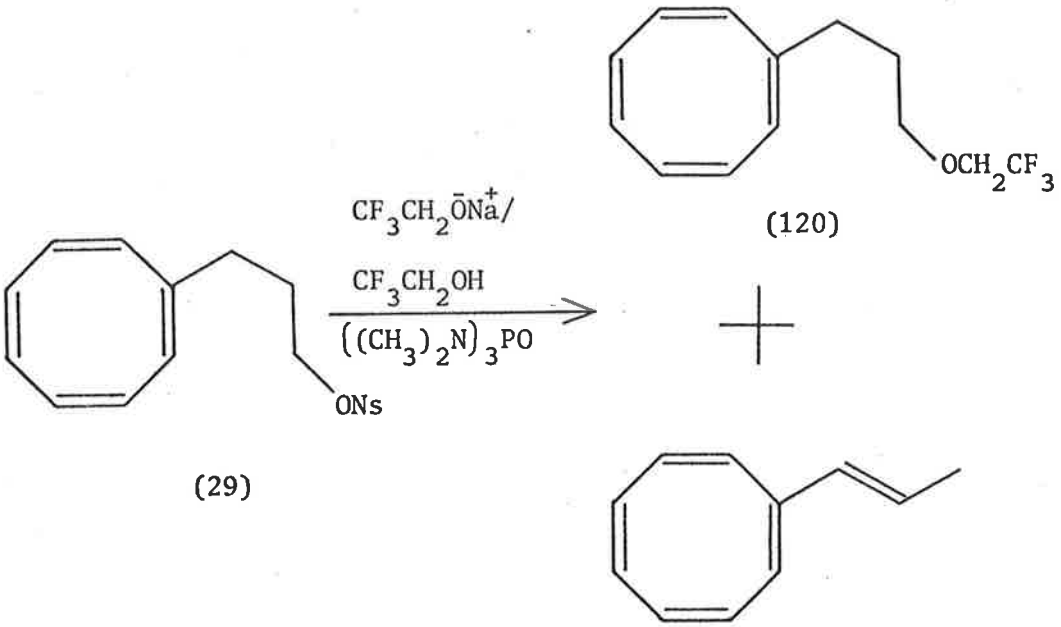


(118)



(119)

3-Cyclooctatetraenylpropyl 2,2,2-trifluoroethyl ether (120) was prepared, in 12% yield, by heating a mixture of the sulphonate (29), sodium 2,2,2-trifluoroethoxide, trifluoroethanol and hexamethylphosphoric triamide. The reaction mixture also contained a mixture of two olefinic compounds (ca. 60:40); the ether could be readily separated from the olefins by dry-column chromatography on silica gel. Preparative g.l.c. of the mixture of olefins gave a pure sample of *E*-1-cyclooctatetraenylprop-1-ene (121), but the other component underwent decomposition on the g.l.c. column. The olefins presumably arise from base catalysed elimination of *p*-nitrobenzenesulphonic acid from the sulphonate (29) to give initially allylcyclooctatetraene; under the basic reaction conditions the double bond presumably moves into conjugation to give (121).

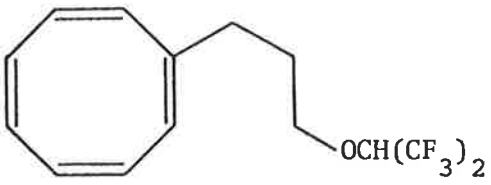


(29)

(120)

(121)

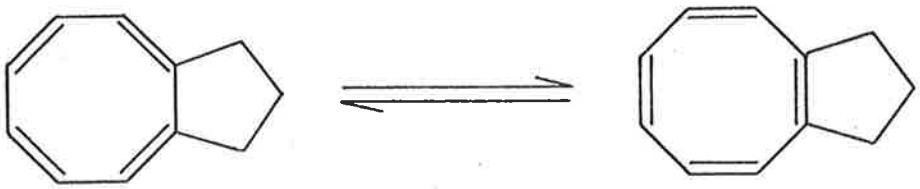
3-Cyclooctatetraenylpropyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (122) was prepared, in 48% yield, by heating a mixture of the sulphonate (29), sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide, hexafluoropropan-2-ol and hexamethylphosphoric triamide.



(122)

cis and *trans*-Bicyclo[6.3.0]undecane were prepared by the reaction sequence shown in Scheme 5. The Stobbe condensation[238,239] of cyclooctanone with diethyl succinate gave the unsaturated keto-ester (123); hydrolysis and decarboxylation[238,239] gave the unsaturated ketone (124). Wolf Kischner reduction to give a mixture of olefins (125) followed by catalytic hydrogenation gave a mixture of *cis* and *trans*-bicyclo[6.3.0]undecane (126); no attempt was made to separate the two isomers. Initially, the reduction of the α,β-unsaturated ketone was attempted using a modified Clemmensen reduction,*[53,240] but an unidentified ketone was obtained.

A sample of bicyclo[6.3.0]undeca-1,3,5,7-tetraene (127)** was available from other work in this department.[241]

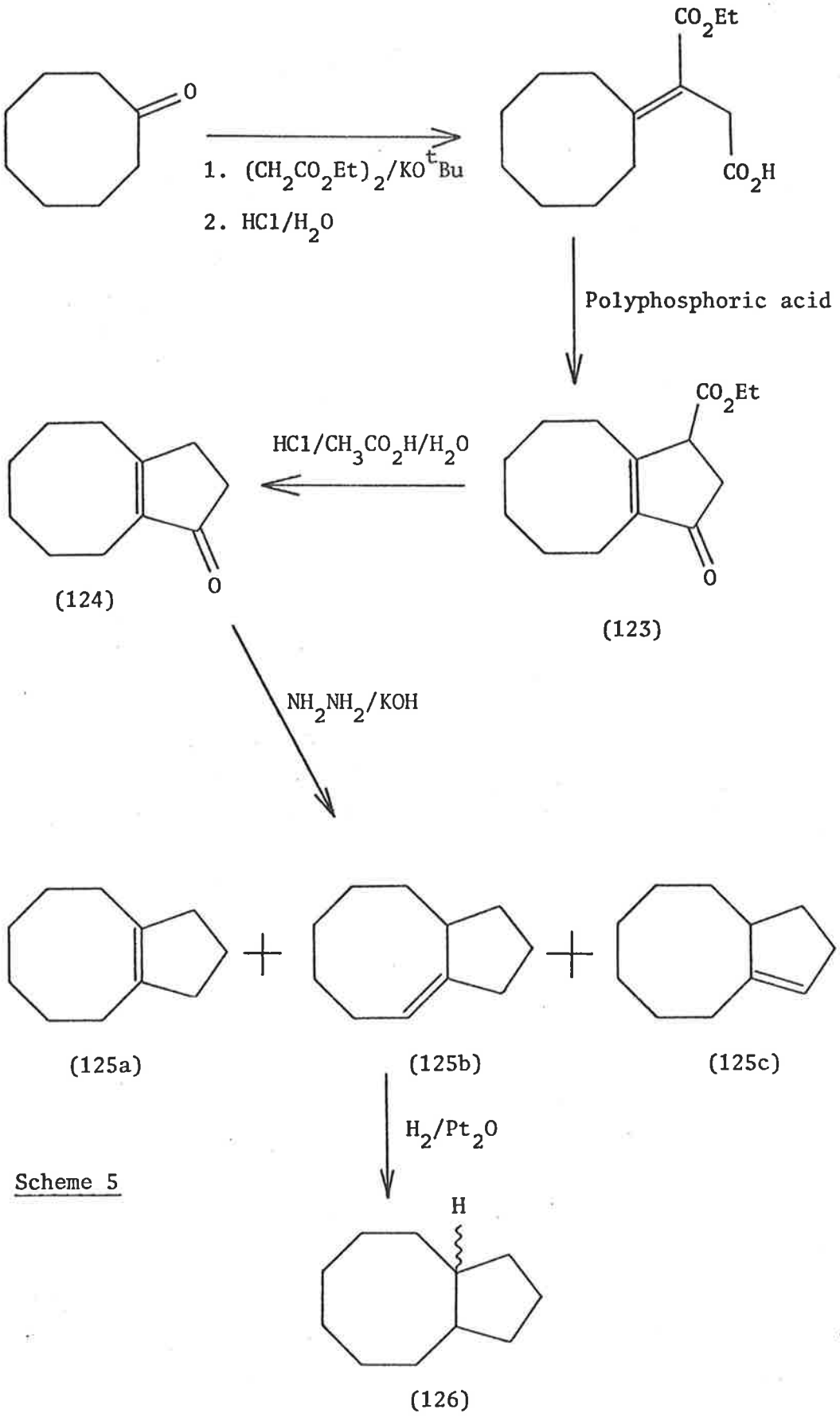


(127a) (127b)

---

* These conditions are reported to reduce completely some α,β-unsaturated ketones to the saturated hydrocarbon.[240]

** Bond shifts can take place in cyclooctatetraene and derivatives.[242,243] The tetraene (127) is expected to exist preferentially as the tautomer (127a) by analogy with other 1,2-disubstituted cyclo-octatetraenes.[242,243]


O
1. $(CH_2CO_2Et)_2/KO^tBu$
2. HCl/H_2O
CO_2Et
CO_2H
Polyphosphoric acid
$HCl/CH_3CO_2H/H_2O$
(124)
(123)
NH_2NH_2/KOH
(125a)
(125b)
(125c)
H_2/Pt_2O
H
(126)

Scheme 5

5.2 Kinetic studies

The rate constants (Table 13) for the solvolysis of 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) in buffered trifluoroethanol and buffered hexafluoropropan-2-ol were determined titrimetrically by the ampoule technique.* Although the ester (29) solvolyses in buffered trifluoroethanol slightly slower than the saturated ester (118) the rate enhancement in trifluoroethanol (0.94) is larger than that in acetic acid (0.60).[53] Since there is almost no π-bond participation for the acetolysis of (29),** we can make the approximation $k_s = 0.60\ k_{sat}$. Using this expression and equation (4),

$$k_t = k_\Delta + k_s \qquad (4)$$

it can be calculated that the extent of cyclization in trifluoroethanol and hexafluoropropan-2-ol should be 36 and 89%, respectively. It must be remembered, however, that the rate of nucleophilic solvent assistance (k_s) for the ester (29) would be more sensitive to the adverse inductive effect of the cyclooctatetraene ring in trifluoroethanol and hexafluoropropan-2-ol than in acetic acid,[52,234] so that the calculated percentages of cyclization represent lower estimates. Using the observed rate retardation for the solvolysis of 4-pentenyl *p*-nitrobenzenesulphonate (26)*** i.e. $k_s = 0.37\ k_{sat}$ (chapter 3), where π-bond participation is insignificant, and taking into account

---

* The more convenient spectrophotometric method could not be used because of overlapping absorptions due to the cyclooctatetraene moieties; the spectrophotometric method (see experimental section, method A) was used for the saturated ester (118).

** Only 1.6% cyclized material was obtained.[53]

*** In hexafluoropropan-2-ol.

p-Nitrobenzene-sulphonate	$10^5 k(s^{-1})$ Buffered acetic acid[A]	Buffered trifluoroethanol	Buffered hexafluoropropan-2-ol
(29)	4.74 4.99	8.69(0.30)[B] 8.88(0.24)	32.3(1.6)[B] 33.2(0.6)
(118)	7.96 8.25	9.32(0.10)[C] 9.42(0.38)	5.89(0.03)[C] 6.05(0.03)
k_{unsat}/k_{sat}	0.60	0.94	5.49

Table 13. Rate constants for the solvolysis of 3-cyclooctatetraenylpropyl and 3-cyclooctylpropyl *p*-nitrobenzenesulphonates at 100°. The values in brackets are standard deviations. A. Data of Gream and Mular;[53] the solutions were initially 0.01M in ester and 0.02M in sodium acetate. B. The solutions were initially 0.01M in ester and 0.02M in triethylamine. C. The solutions were initially 0.0025M in ester and 0.01M in triethylamine.

the greater inductive effect of a cyclooctatetraene ring than a double bond,[53] we arrive at $k_s = 0.37 \times 0.75\ k_{sat}$ i.e. $k_s = 0.28\ k_{sat}$. Using this value, the calculated percentage of cyclization for the solvolysis of (29) in buffered hexafluoropropan-2-ol is 95%; this figure is still less than the observed value (99.5%). This discrepancy might possibly be the result of participation by neighbouring carbon or hydrogen during the solvolysis of 3-cyclooctylpropyl and/or *n*-pentyl *p*-nitrobenzenesulphonates in hexafluoropropan-2-ol.*

5.3 Product studies

The yields of the products from the solvolysis of the ester (29) in buffered trifluoroethanol and buffered hexafluoropropan-2-ol are reported in Table 14; the relative yields for the products from the acetolysis of the ester (29) are shown for comparison.[53]

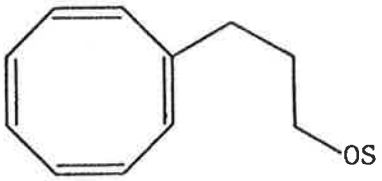
---

* Neighbouring carbon and hydrogen participation in solvolysis has recently been shown to be much more important than previously thought.[4]

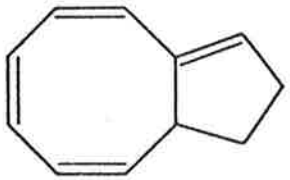
Product	% Buffered acetic acid[A]	Buffered trifluoroethanol[B]	Buffered hexafluoropropan-1-ol[B]
(128)	97.4	27(27)	0.5(0.5)
(119)	1.0	trace	trace
(57)	1.6[C]	39(73)	67(99.5)
(127)	0	0	0
% cycl.	1.6	39(73)	67(99.5)

Table 14. Products from the buffered solvolysis of 0.01M solutions of 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) in acetic acid, trifluoroethanol and hexafluoropropan-2-ol after 10 half-lives at 100°. The yields in brackets are the relative yields based on the tetraene (57) being the only product that is unstable to the conditions of the solvolysis. A. Data of Gream and Mular;[53] the acetic acid contained 0.02M sodium acetate. B. Containing 0.02M triethylamine. C. This product was previously postulated to be the tetraene (127).[53] In the present work, the cyclized product from the acetolysis was shown to be the tetraene (57) by g.l.c. comparison with an authentic sample.

The trifluoroethyl ether (120), hexafluoroprop-2-yl ether (122) and allylcyclooctatetraene (119) were identified by g.l.c. comparison with authentic samples. The trifluoroethyl ether (120) was also isolated



(128)



(57)

S = $-COCH_3$

or $-CH_2CF_3$ (120)

or $-CH(CF_3)_2$ (122)

from the solvolysis mixture; it could be readily separated from olefinic products by preparative t.l.c. on silica gel. The major product from the solvolysis in both trifluoroethanol and hexafluoropropan-2-ol was shown to be bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57); this compound has not been previously isolated. This tetraene (57) could be readily separated from the other solvolysis product and polymer by preparative t.l.c. or dry column chromatography on silica gel. It polymerized very readily especially upon concentration; thus care was taken to avoid concentration wherever possible. It also polymerized in ether or low boiling petroleum, even at -15°.

Evidence for the structure (57) was obtained from its mass spectrum (m/e 144) and ^1H and ^{13}C n.m.r. spectra. Accurate mass measurement of the molecular ion confirmed the molecular formula as did the formation of an adduct $C_{17}H_{12}N_4$ with tetracycanoethylene

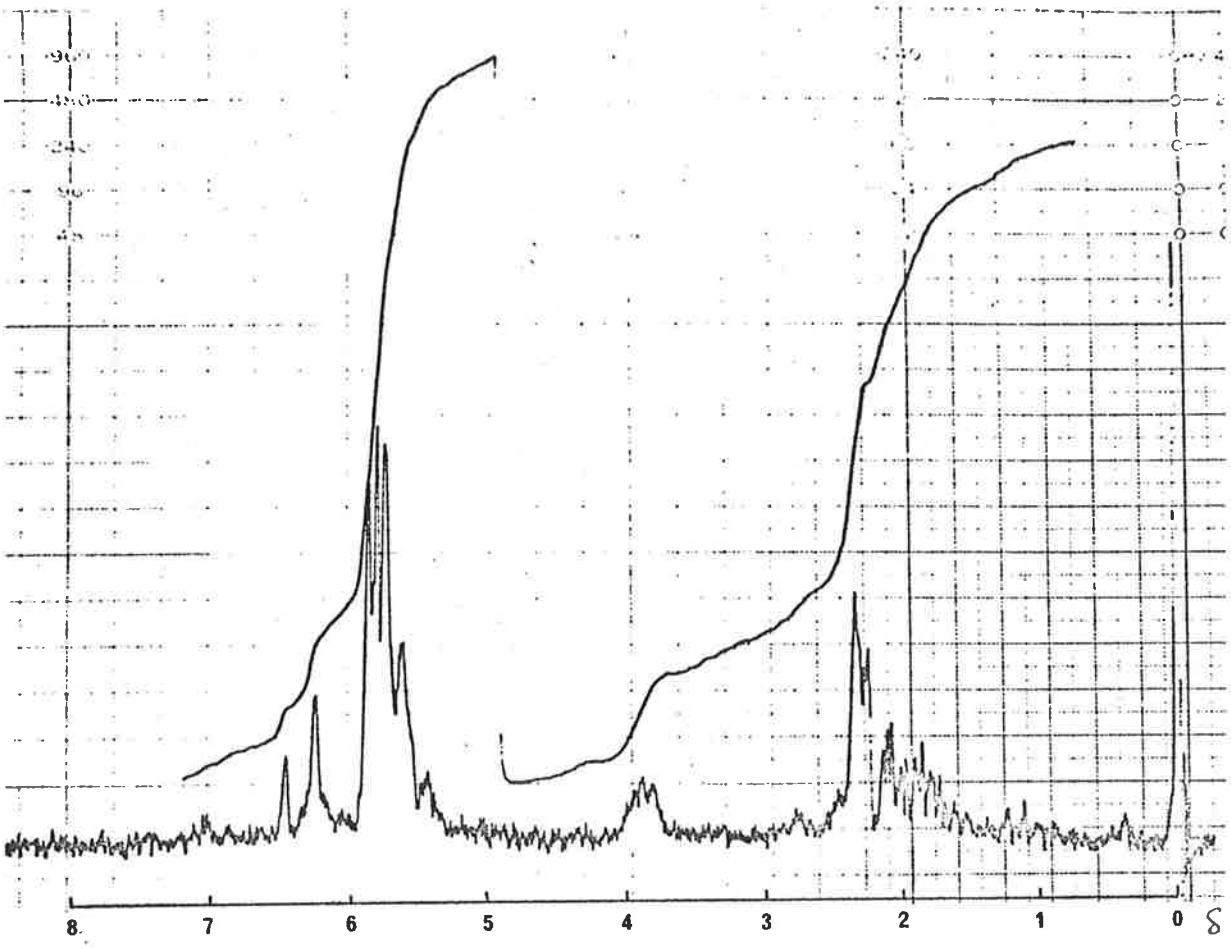


Fig. 1. 60MHz ^{1}H n.m.r. spectrum of bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57)

(see Chapter 7). The ^{1}H n.m.r. spectrum (Fig. 1) shows resonances for 7 olefinic hydrogen atoms (δ5.6-6.3), 1 bisallylic hydrogen (3.86) and 4 alicyclic hydrogen atoms (1.6-2.4). The ^{13}C n.m.r. spectrum (Fig. 2) shows resonances for 8 olefinic carbon atoms (δ124-145) and 3 saturated carbon atoms (δ30-45); the resonance at δ145 is assigned to C8 on the basis of its high chemical shift and its low intensity which is characteristic of quaternary carbon atoms.

No trace of the tetraene (127) could be detected in the products from the solvolysis of (29) in either trifluoroethanol or hexafluoropropan-2-ol.

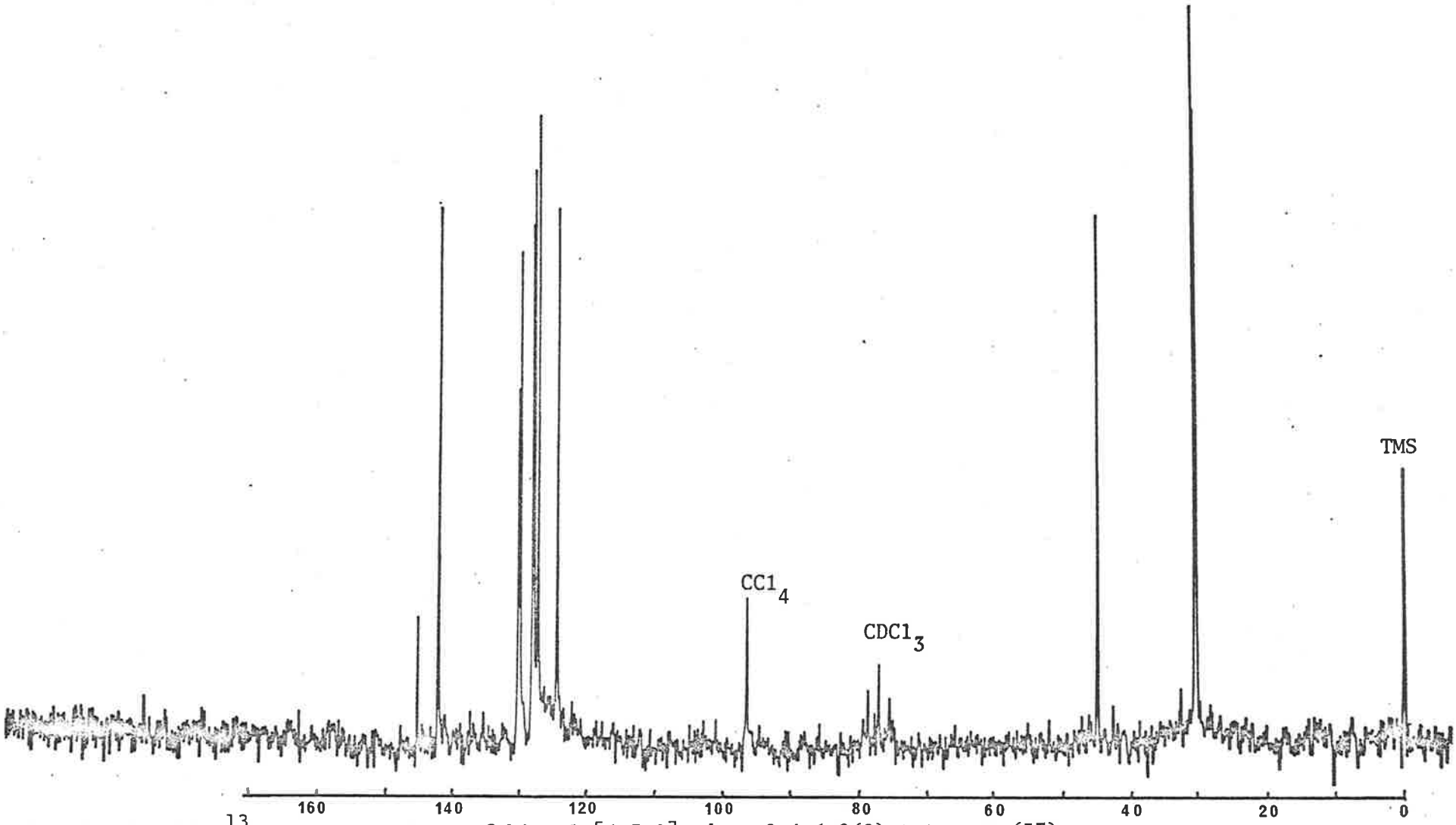


Fig. 2. 20.1MHz ^{13}C n.m.r. spectrum of bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57).

The low recovery of products (67%) is probably due to the polymerization of the tetraene (57) during the solvolysis and/or the working-up process. In support of this, samples of the trifluoroethyl ether (120), allylcyclooctatetraene (119) and bicyclo[6.3.0]undeca-1,3,5,7-tetraene (127) were quantitatively recovered unchanged after being subjected to the trifluoroethanolysis conditions. In hexafluoropropan-2-ol, the hexafluoroprop-2-yl ether (122), allylcyclooctatetraene (119) and the tetraene (127) were all recovered unchanged after being subjected to the solvolysis conditions.

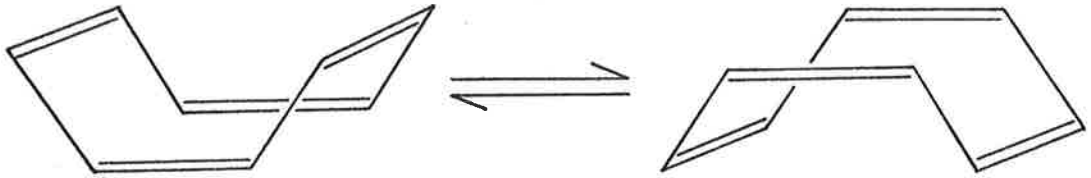
Catalytic hydrogenation of the product mixtures from the solvolysis of (29) in buffered trifluoroethanol and buffered hexafluoropropan-2-ol gave a mixture of two hydrocarbons; these two hydrocarbons were shown to be *cis* and *trans*-bicyclo[6.3.0]undecane (126) by comparison with samples prepared by independent synthesis (section 5.1). The yield was 41% in the case of the products from solvolysis in trifluoroethanol and for hexafluoropropan-2-ol 46%.

5.4 Discussion

Both kinetic and product studies (Tables 13 and 14) show that extensive π-bond participation occurs for the solvolysis of 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) in buffered trifluoroethanol and buffered hexafluoropropan-2-ol. The extent of such participation (73% in trifluoroethanol and 99.5% in hexafluoropropan-2-ol) is in contrast to the 1.6% of cyclized product found for the acetolysis of (29)[53] and again illustrates the usefulness of trifluoroethanol and hexafluoropropan-2-ol for inducing cyclizations *via* the π-route.

Before postulating any mechanisms or intermediates for π-bond participation in (29), some of the properties of cyclooctatetraene and its derivatives need to be illustrated.*

The eight membered ring of cyclooctatetraene exists in a non-planar "tub" form (129)[248-250] and at ordinary temperatures the molecule undergoes rapid ring inversions (equation 9).[251-255]



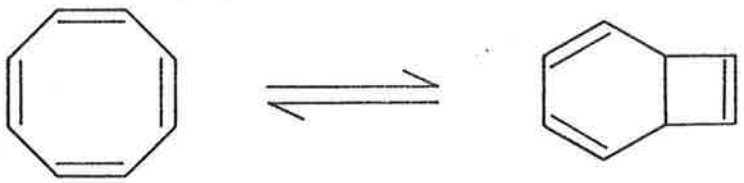
(9)

(129)

In addition to this conformational change, two kinds of valence tautomerism occur. The first involves bond shifts in the eight-membered ring, the single and double bonds exchanging their position.[242-245] The second type of valence tautomerism displayed by cyclooctatetraene results in a low concentration (ca. 0.01% at 100°) of bicyclo[4.2.0]-octa-2,4,7-triene (equation 10).[244,256-258] A monosubstituted cyclo-octatetraene may exist in equilibrium with one or more of the four possible valence tautomers (130-133).[259,260] The nature of the

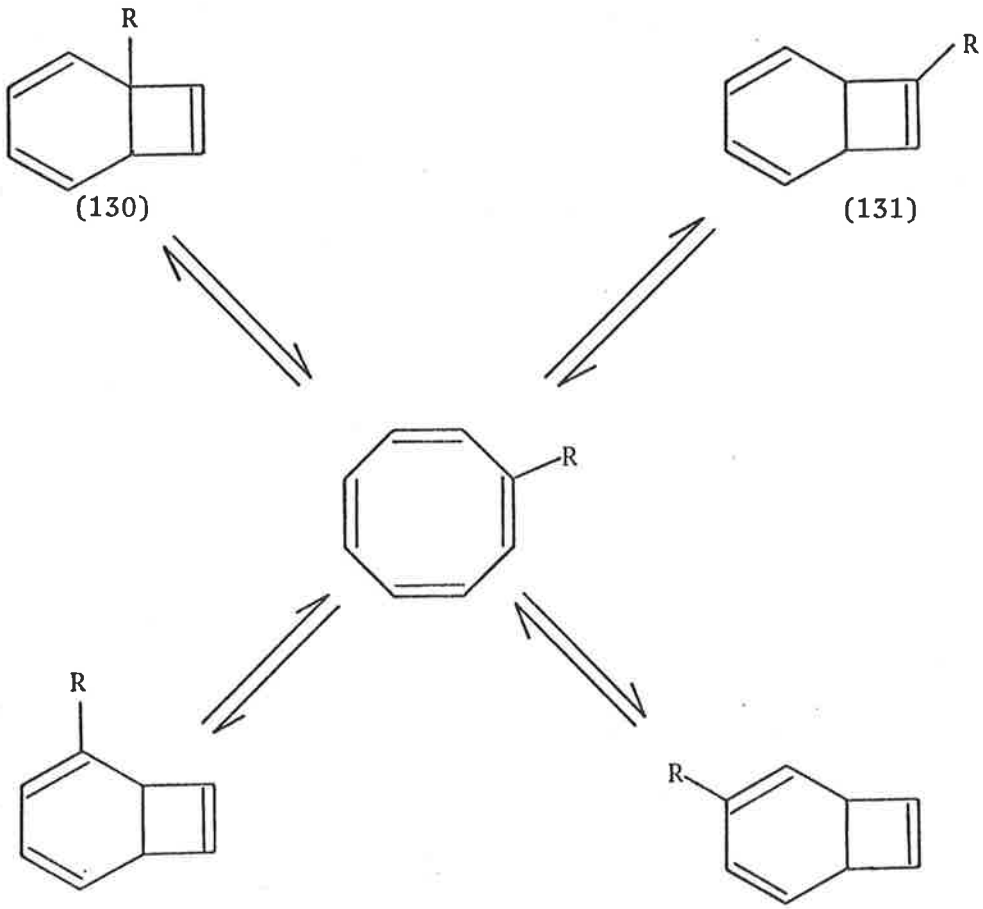
---

* Reviews by Paquette[246] and Fray and Saxton[247] have appeared recently.



(10)

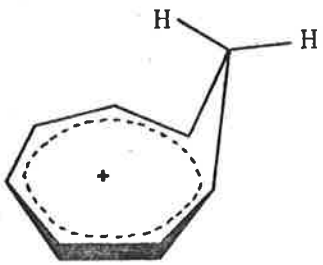
substituent, R, is very important in determining which of the valence tautomers will be favoured.[260] When R = alkyl, the tautomer (131) is kinetically favoured and this tautomer is the one that is predominantly or exclusively trapped by dienophiles.[260]



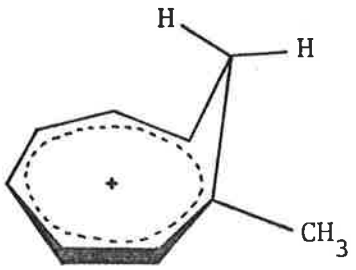
(130) (131)

(132) (133)

Cyclooctatetraene readily reacts with acid and other electrophiles to form the stabilized homotropylium ion (134)[261-268] whose structure is based on compelling spectral evidence.[263,269-271]



(134)

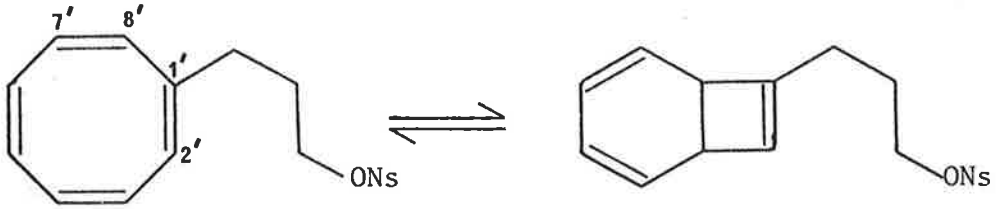


(135)

Methylcyclooctatetraene reacts with acid to form the homotropylium ion (135) to the exclusion of the other possible isomers.[272] The formation of homotropylium ions from other substituted cyclooctatetraenyl derivatives has also been reported.[273-278] Crystalline homotropylium salts have been formed by treating cyclooctatetraene with antimony V chloride in the presence of hydrogen chloride or hydrogen bromide.[262,279]

The mechanism of π-bond participation during the solvolysis of 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) in trifluoroethanol and hexafluoropropan-2-ol will now be considered. Remembering that the transition state for double bond participation requires that the carbon bearing the leaving group be located directly over the double bond in the plane of the π-orbitals, π-bond participation for (29) can occur by 3 different pathways i.e.

participation by the 1',2' double bond, the 7',8' double bond or the cyclobutenyl double bond of the bicyclic form of (29) i.e. (136); each of these pathways will be considered in turn.

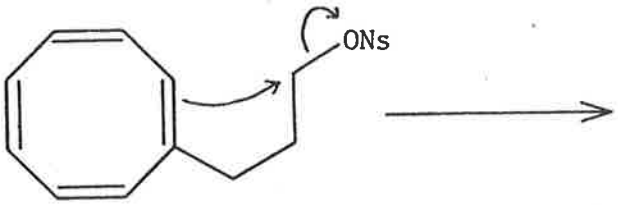


(29) (136)

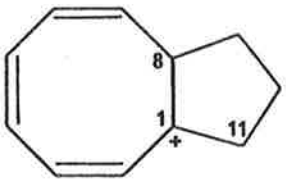
(i) The double bond in the 4,5-position from the leaving group (the 1',2'-bond) may participate in a manner analogous to that in 3-(cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate (27) (Chapter 3). The non-planar species (137) would be initially formed but 'leakage' to the planar cyclooctatetraenyl ion (138) and/or the homotropylium ion (139)* may occur. Similar homotropylium ions to (139) have been considered by Gream and Mular[53] as possible intermediates for the acetolysis of 2-cyclooctatetraenylethyl *p*-nitrobenzenesulphonate (140a)

---

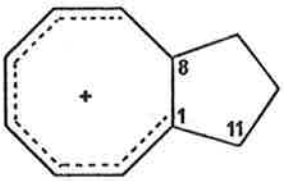
* Winstein and co-workers[270] have calculated that a homoaromatic monohomotropylium ion has a free energy that is 93.2 kJ mol^{-1} less than that of a planar cyclooctatetraenyl cation. Jorgensen[280] has calculated from molecular orbital calculations that the homoaromatic stabilization of a monohomotropylium ion is 41-63 kJ mol^{-1}.



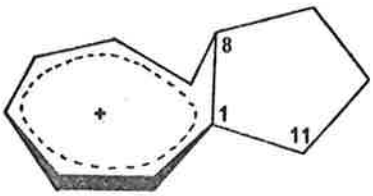
(29)



(137) and/or

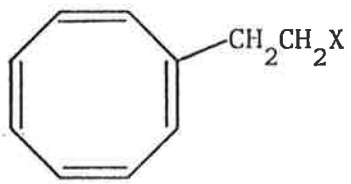


(138) and/or

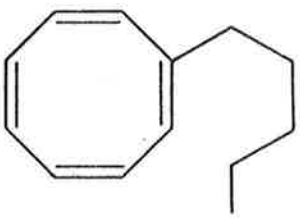


(139)

and 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) and by Paquette[27,267] for the solvolysis of 2-cyclooctatetraenylethyl *p*-bromobenzenesulphonate (140b).



(140)

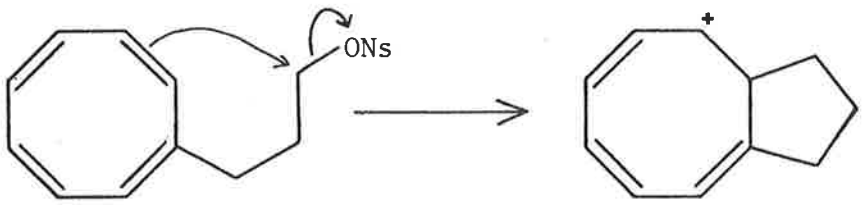


(21)

a, X = ONs

b, X = OBs

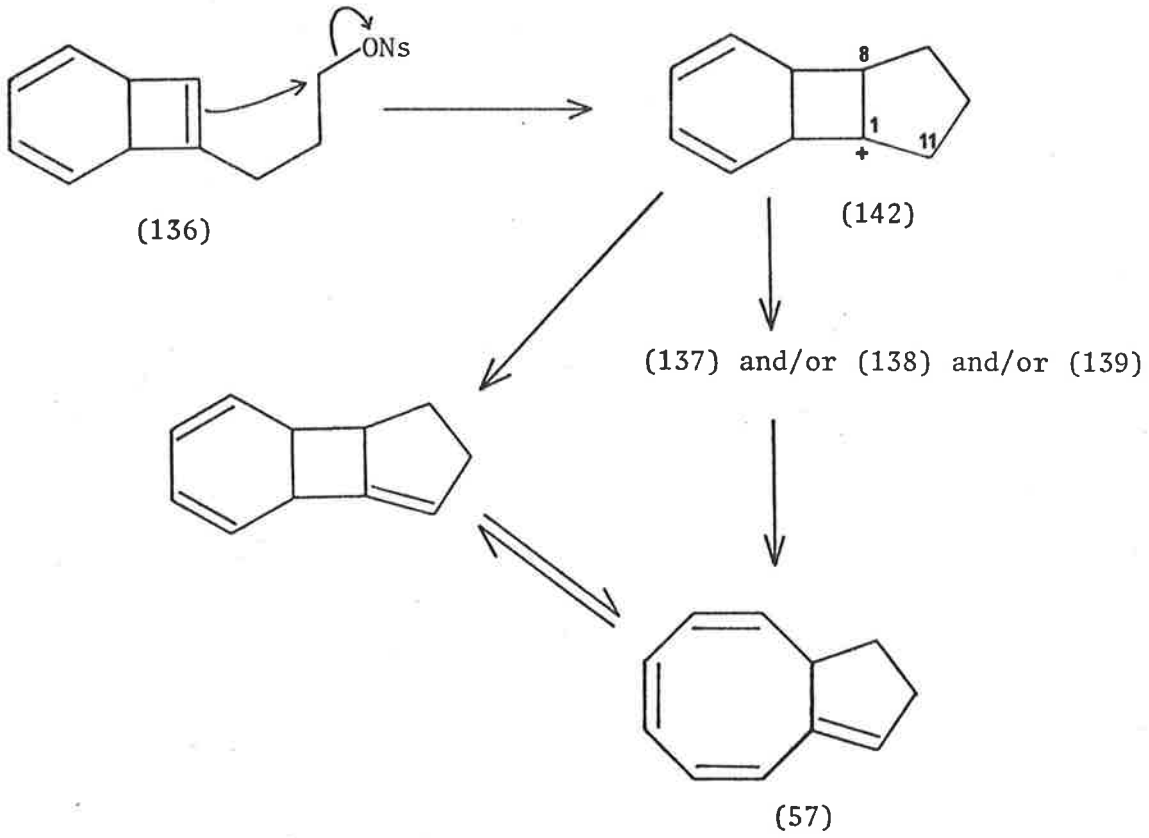
(ii) Examination of models show that the carbon bearing the leaving group can approach the plane of the π-orbitals of the 7',8'-double bond more closely than that of the 1',2'-double bond;[53] the 7',8'-double bond is in the more favourable 5,6-position relative to the leaving group, but the initially formed ion would be the less



(29) (141)

stable secondary ion (141). The ion (141), however, may give rise to ions (137) and/or (138) and/or (139) by charge delocalization; it should be noted that the observed cyclized product (57) cannot directly be formed from the ion (141).

(iii) Double bond participation may occur through the bicyclic tautomer (136); the initially formed ion (142) could either lose a proton to give the tricyclic tautomer of the tetraene (57) or undergo a disrotatory ring opening to give the ions (137) and/or (138) and/or (139). An indication that this route is energetically feasible comes from the free energies of activation for the solvolysis of (29) in trifluoroethanol and hexafluoropropan-2-ol. The respective values

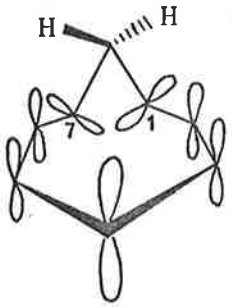


of 121 and 117 kJ mol^{-1} at 100° are higher than the free energy of activation for the valence isomerization of ethylcyclooctatetraene at 100° i.e. 112 kJ mol^{-1}.[281]

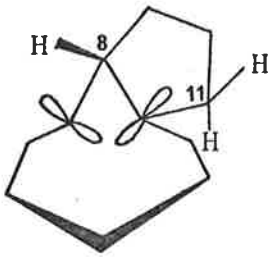
The most striking observation concerning the products from the solvolysis of (29) in trifluoroethanol and hexafluoropropan-2-ol is the formation of bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57) to the exclusion of bicyclo[6.3.0]undeca-1,3,5,7-tetraene (127). Two possible rationalizations for this fact can be considered:
(a) the loss of a proton regiospecifically from C11 in the homotropylium ion intermediate (139) may be rationalized by orbital overlap considerations, and (b) the counter-ion in the initially formed ion-pairs of the intermediate ions (137) and/or (138) and/or (139) and/or (142) may be more favourably located to abstract a proton from C11 than

from C8. Both of these rationalizations will now be considered in more detail.

(a) The postulated arrangement of orbitals at C1 and C7 for a homotropylium ion involves p-p overlap as shown in structure (143);[267,280] if a similar arrangement is postulated for the homotropylium ion (139)



(143)



(144)

i.e. (144), then one of the C-H bonds on C11 lies approximately in the same plane as the p orbital on C1.* On the other hand, the C-H bond at C8 is nearly perpendicular to the plane of the p orbital on C1. Consideration of the other possible intermediate ions i.e. (137), (138) and (142) shows that both the hydrogen at C8 and one of the hydrogens at C11 are coplanar or nearly coplanar with the vacant p orbitals at C1.

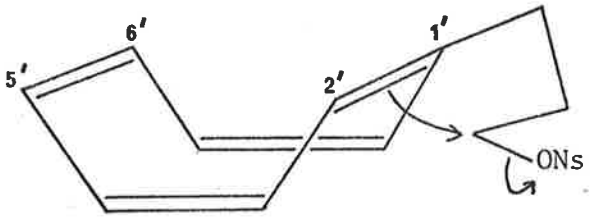
(b) In order to consider the ion-pairs that would be initially formed from the solvolysis of (29) *via* the π-route, it is necessary to

---

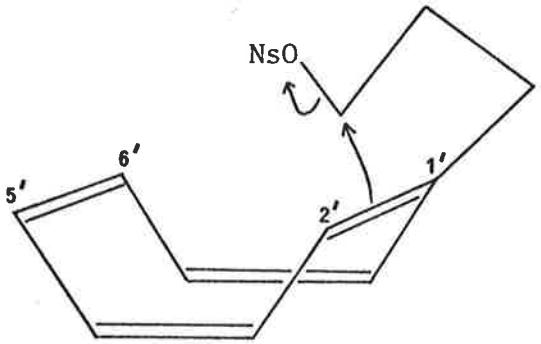
* See footnote p. 72.

consider each of the possible mechanisms i.e. (i)-(iii) above.

Considering participation by the 1',2'-double bond, there are two possible ways it can cyclize i.e. (145) and (146). In (145),

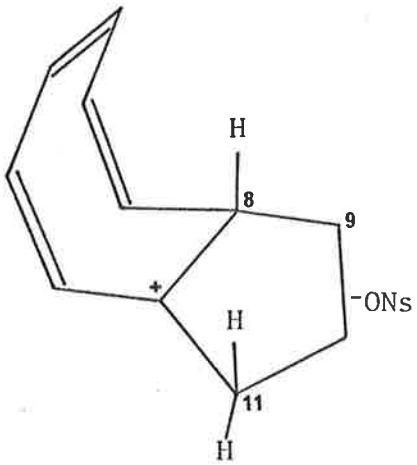


(146)

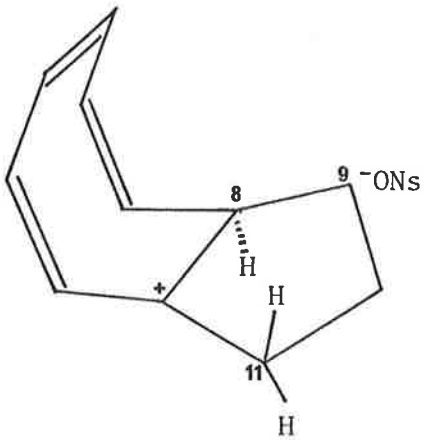


(145)

unfavourable interactions due to the 5',6'-double bond should seriously hinder cyclization *via* (145). On the other hand, in (146), there are no serious steric interactions which might hinder cyclization. Cyclization *via* (145) and (146) would give the ion-pairs (147) and (148), respectively; in



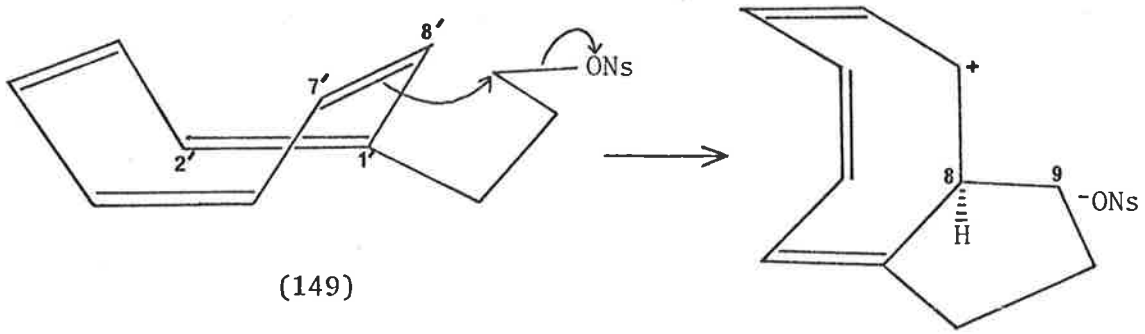
(148)



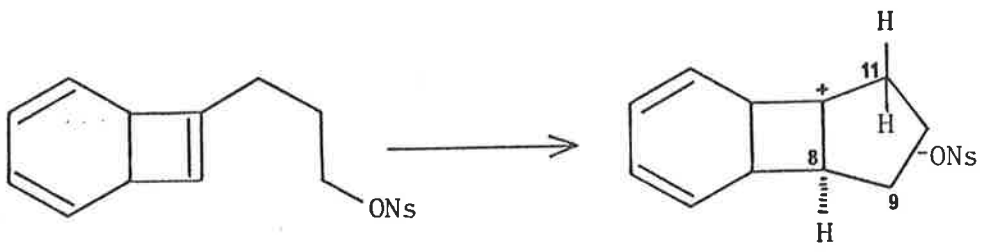
(147)

both ion-pairs the counter-ion is in the vicinity of C9 but on the opposite side of the molecule to the hydrogen at C8. For the counter-ion to act as a base it only has to move a short distance to abstract a proton at C11; on the other hand, the counter-ion would have to move to the opposite side of the molecule to abstract a proton at C8.

Cyclization *via* participation by the 7',8'-double bond (149) would initially give the ion-pair (150), whilst reaction through the bicyclic tautomer (136) would initially give the ion-pair (151). In both of these ion-pairs, (150) and (151), the counter-ion is on the opposite side of the molecule to the hydrogen at C8. In (151) the counter-ion only has to move a short distance to abstract a proton from



(149) (150)



(136) (151)

C11. The ion-pair (150), however, cannot directly give the olefin (57) without delocalization of positive charge. Any of the ion-pairs (147), (148), (150) or (151) may undergo charge delocalization to give ions (138) and/or (139); the homotropylium ion (139) appears to be a more likely intermediate in view of its added stability. Furthermore, if delocalization to the homotropylium ion intermediate (139) occurs, then abstraction of a proton from C8 is precluded as explained above.

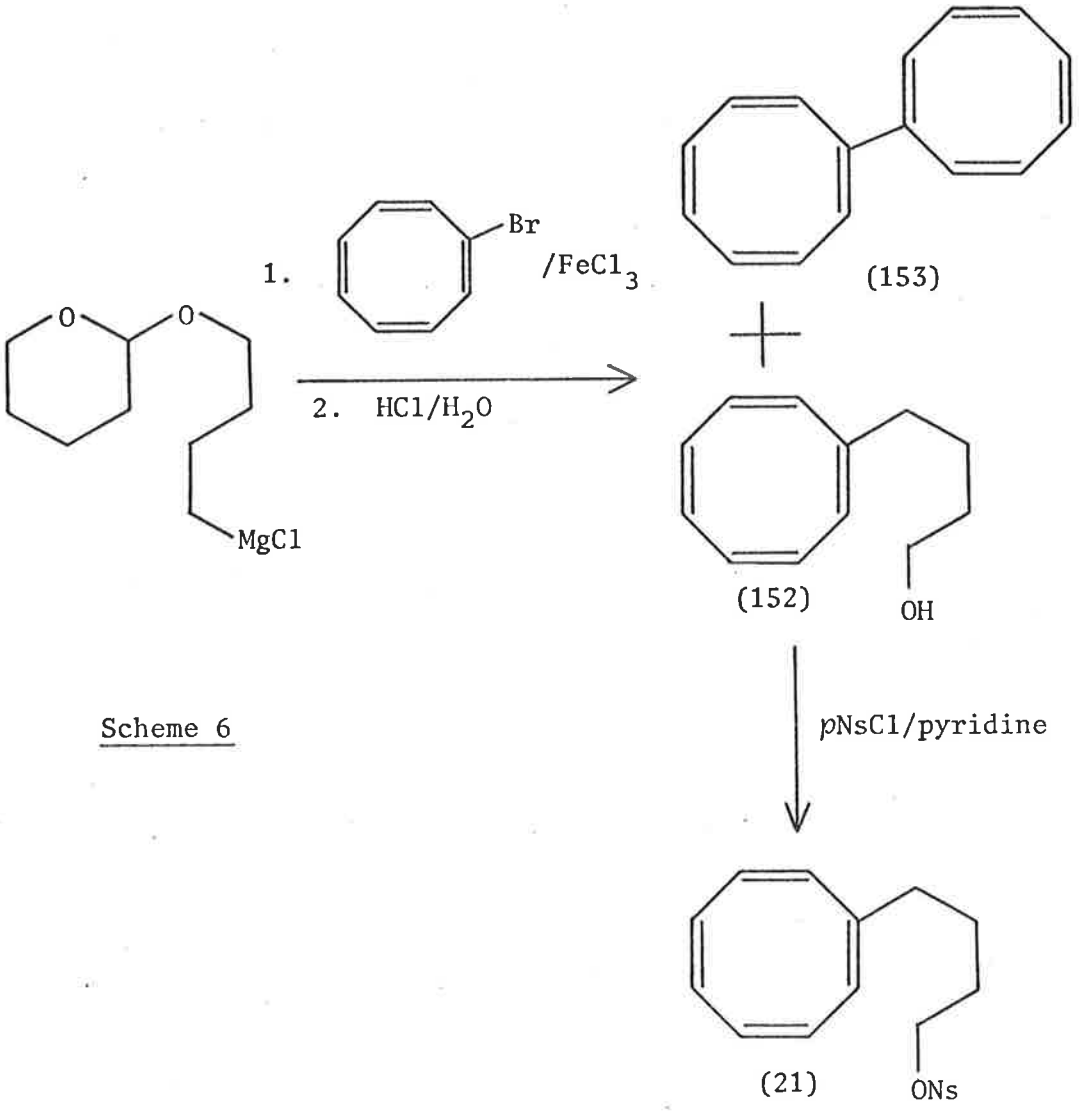
In summary, 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) solvolyses in buffered trifluoroethanol and hexafluoropropan-2-ol with extensive π-bond participation; this result is in contrast to the use of acetic acid where minimal π-bond participation has been reported.[53] The only product that is detected from the solvolysis of (29) *via* the π-route is bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57). The exclusive formation of this product may be accounted for by the formation of a homotropylium ion intermediate or by proton abstraction by the counter-ion in ion-pairs; the solvolysis mechanism might involve both of these factors.

CHAPTER 6

The solvolysis of 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate in trifluoroethanol and hexafluoropropan-2-ol

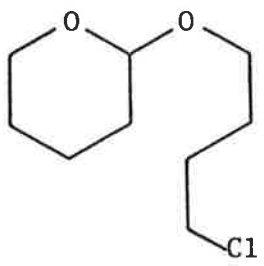
6.1 Synthesis of the required materials

4-Cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) was synthesized as shown in Scheme 6. Treatment of 4-(tetrahydropyran-2'-yloxy)butylmagnesium chloride with bromocyclooctatetraene in the presence of a catalytic amount of anhydrous ferric chloride[282] gave, after hydrolysis, a mixture of 4-cyclooctatetraenylbutanol (152) and biscyclooctatetraene (153). Separation by chromatography on silica gel, followed by distillation, gave the required alcohol (152) in

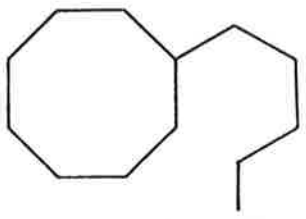


Scheme 6

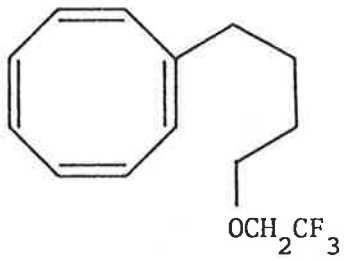
42% yield.* Treatment of cyclooctatetraenylmagnesium bromide with 1-chloro-4-(tetrahydropyran-1'-yloxy)butane (154) in the presence of ferric chloride did not give any of the required alcohol (152) after hydrolysis. 4-Cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) was prepared from the alcohol (152) as previously described.[53]



(154)



(155)



(156)

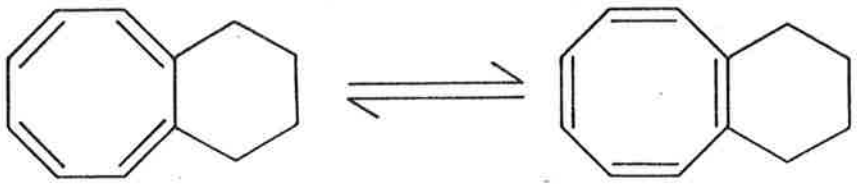
4-Cyclooctylbutyl *p*-nitrobenzenesulphonate (155) was available from earlier work in this department.[53] 4-Cyclooctatetraenylbutyl 2,2,2-trifluoroethyl ether (156) was prepared in low yield from the treatment of the ester (21) with sodium 2,2,2-trifluoroethoxide in trifluoroethanol and hexamethylphosphoric triamide.

A sample of bicyclo[6.4.0]dodeca-1,3,5,7-tetraene (157)** was available from other work in this department.[241]

---

* This method of preparation of (152) represents an improvement in both yield and convenience over the method of Gream and Mular;[53] the method used by these workers involved 6 steps and the overall yield of alcohol (152) was 28%.[53,283]

** See footnote p. 84 and also reference 53.



(157a) (157b)

6.2 Kinetic studies

The rate constants for the solvolysis of 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) and 4-cyclooctylbutyl *p*-nitrobenzenesulphonate (155) in buffered trifluoroethanol (Table 15) and buffered hexafluoropropan-2-ol (Table 16) were determined titrimetrically by the ampoule technique.*

The rate enhancements for the solvolysis of (21) in buffered trifluoroethanol (k_{unsat}/k_{sat} = 13.4) and buffered hexafluoropropan-2-ol (k_{unsat}/k_{sat} = 151) suggest that solvolysis occurs with extensive π-bond participation. The degree of anchimeric assistance in these two solvents is much greater than that reported for the solvolysis of (21) in buffered acetic acid (k_{unsat}/k_{sat} = 1.59).[53]

---

* See footnote p. 85; the spectrophotometric method was used for the saturated ester (155).

p-Nitrobenzenesulphonate	T(°C)	$10^5k(s^{-1})$	k_{unsat}/k_{sat}
4-cyclooctatetraenylbutyl (21)[A]	60.0	3.20(0.10) 3.36(0.07)	
	70.0	8.23(0.12) 8.57(0.09)	
	80.0	19.2(0.3) 19.9(0.3)	
	100.0	95.9[C]	13.4
4-cyclooctylbutyl (155)[B]	100.0	7.07(0.10) 7.25(0.05)	

Table 15. Rate constants for the solvolysis of (21) and (155) in trifluoroethanol. The values in brackets are standard deviations. A. The solutions were initially 0.01M in ester and 0.02M in triethylamine; activation parameters, $\Delta H^{\neq}$ 83.9±1.5 kJ mol^{-1}, $\Delta S^{\neq}$ -79.7±4.3 JK^{-1} mol^{-1}. B. The solutions were initially 0.0025M in ester and 0.01M in triethylamine. C. Extrapolated.

p-Nitrobenzenesulphonate	T(°C)	$10^5 k(s^{-1})$	k_{unsat}/k_{sat}
4-cyclooctatetraenylbutyl (21)[A]	30.0	2.84(0.05) 2.92(0.25)	
	40.0	6.16(0.18) 6.17(0.32)	
	50.0	15.6(0.6) 15.9(0.6)	
	100.0	467[C]	151
4-cyclooctylbutyl (155)[B]	100.0	3.09(0.03) 3.10(0.02)	

Table 16. Rate constants for the solvolysis of (21) and (155) in hexafluoropropan-2-ol. The values in brackets are standard deviations. A. The solutions were initially 0.01M in ester and 0.02M in triethylamine; activation parameters, $\Delta H^{\neq}$ 66.4±2.7 kJ mol^{-1}, $\Delta S^{\neq}$ -113±9 JK^{-1} mol^{-1}. B. The solutions were initially 0.0025M in ester and 0.01M in triethylamine. C. Extrapolated.

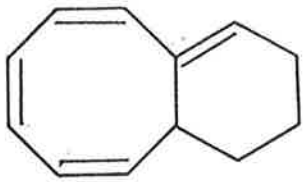
The predicted extent of cyclization during the solvolysis of (21), using equation (4) and assuming $k_s = 0.65\, k_{sat}$,[53] is 95% in trifluoroethanol and 99.6% in hexafluoropropan-2-ol, in close agreement with the observed values i.e. 94.1 and 100%, respectively (see later). In view of the expected greater effectiveness of the adverse inductive effect of the cyclooctatetraene ring upon k_s for the solvolysis of (21) in trifluoroethanol and hexafluoropropan-2-ol compared to acetic acid (see pages 67, 78 and 85), the closeness of the predicted and found values is surprising. It should be noted, however, that the found and predicted values (based on the effects of inductive effects upon rate constants in acetic acid) should be (and are - see p. 85) in closer agreement for (21) than for (29); this results from the cyclooctatetraenyl ring being further removed from the carbon bearing the leaving group in (21) than in (29).

6.3 Product studies

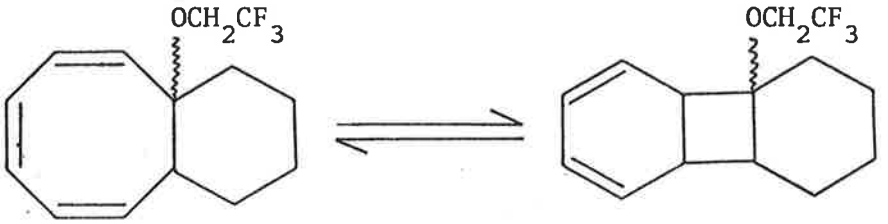
The yields of the products from the solvolysis of the ester (21) (after 10 half-lives) in buffered trifluoroethanol and buffered hexafluoropropan-2-ol are reported in Table 17; the relative yields of products from the acetolysis of (21) are shown for comparison.

4-Cyclooctatetraenylbutyl 2,2,2-trifluoroethyl ether (156) and bicyclo[6.4.0]dodeca-1,3,5,7-tetraene (157) were identified by g.l.c. comparison with authentic samples.

A mixture of the two isomers of 1-(2',2',2'-trifluoroethoxy)-bicyclo[6.4.0]dodeca-2,4,6-triene (158) was isolated from the solvolysis of (21) in trifluoroethanol. They were separated from the other

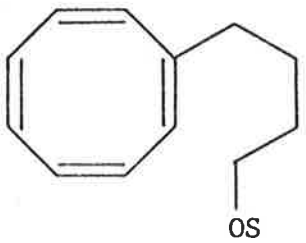


(58)



(158) (11)

solvolysis products by preparative t.l.c. on silica gel; no attempt was made to separate the two isomers. The ^{1}H n.m.r. spectrum indicated that both isomers were present in both valence tautomers (equation 11).



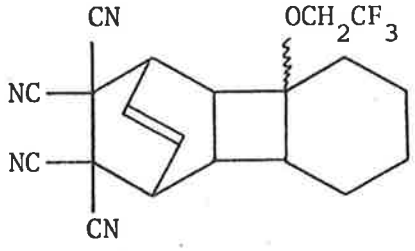
S = $-COCH_3$
or $-CH_2CF_3$ (156)
or $-CH(CF_3)_2$

(159)

Product	Buffered acetic acid[A]	% Buffered trifluoroethanol[B]	Buffered hexafluoropropan-2-ol[B]
(159)	56.2	5.9(5.9)[C]	0
(157)	2.6	3.5(3.9)	1.2
(58)	40.3	28.9(90.2)	98.8
(158)[D]		61.7(0)	
unknown	0.9		
% cycl.	43	94.1(94.1)	100.0

Table 17. Products from the solvolysis of 0.01M solutions of 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) in acetic acid, trifluoroethanol (80.0°) and hexafluoropropan-2-ol (40.0°). A. Data of Gream and Mular;[53] the acetic acid contained 0.02M sodium acetate. B. Containing 0.02M triethylamine. C. The values in brackets are the percentages of products 5 min. after a trace of *p*-toluenesulphonic acid had been added to an ethereal solution of the products from the solvolysis of (21) in buffered trifluoroethanol. D. Two isomers were present (59:41).

Treatment of the mixture of ethers (158) with tetracyanoethylene gave an adduct, $C_{20}H_{17}F_3N_4O$, in 96% yield. Spectral data of this adduct were consistent with the structure (160); no attempt was made to determine the stereochemistry of the mixture of adducts (160). Further evidence for the structure (158) comes from its acid catalysed elimination of trifluoroethanol to give almost exclusively bicyclo[6.4.0]dodeca-2,4,6,8(9)-tetraene (58) (see Table 17).

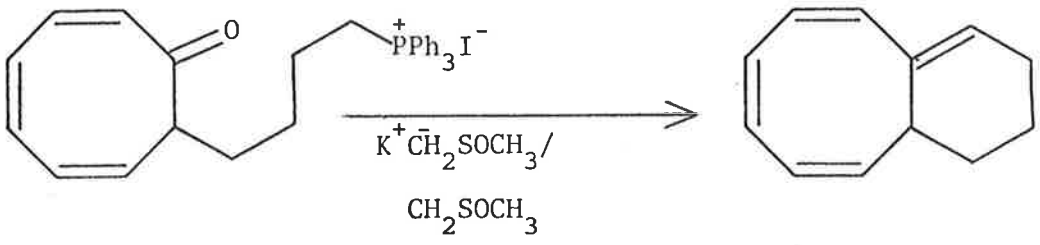


(160)

The tetraene (58) had been tentatively identified on the basis of indirect evidence as a product of the acetolysis of (21);[53] despite previous attempts,[53,284] this olefin (58) has not been previously characterized. In the present work, however, the tetraene (58) was isolated as the major product from the solvolysis of (21) in hexafluoropropan-2-ol. The infrared, ^1H n.m.r. (Fig. 3) and ^{13}C n.m.r. (Fig. 5) spectra were consistent with the structure (58). The ^1H n.m.r. spectrum was consistent with the presence of 7 olefinic hydrogen atoms (δ5.5-6.1),

1 bisallylic hydrogen (3.8) and 6 alicyclic hydrogen atoms (1.5-2.3); the ^{13}C n.m.r. spectrum indicated 8 olefinic carbon atoms (δ121-143) and 4 alicyclic carbons (18-35). Treatment of the tetraene (58) with tetracyanoethylene gave a white solid, $C_{18}H_{14}N_4$, in 97% yield from the sulphonate (21); this white solid was later shown to be a mixture of 3 adducts (see Chapter 7).

The structure (58) was also confirmed by independant synthesis.* Treatment of 4-(2'-oxocycloocta-3',5',7'-trienyl)butyltriphenylphosphonium iodide (161)[284] with potassium methylsulphinylmethide in dimethylsulphoxide gave a yellow oil which was purified by column chromatography on silica gel. The product obtained exhibited an ^1H n.m.r. spectrum (Fig. 4) which was essentially identical to that of the tetraene (58) obtained *via* solvolysis.** Accurate mass measurement of its molecular ion confirmed the molecular formula. Treatment of the product formed in



(161) (58)

---

* In earlier work in this department,[284] it was reported that a product (4% yield by g.l.c.) from the Wittig reaction of the phosphonium salt (161) had identical g.l.c. characteristics to the acetolysis product tentatively identified as (58). This product or its tetracyanoethylene adduct could not be isolated in this earlier work.[284]

** The chemical shifts of the resonances in the two spectra (Figs. 3 and 4) differ slightly; this is probably the result of concentration differences and the presence of impurities. Furthermore, the two spectra were recorded on different spectrometers.

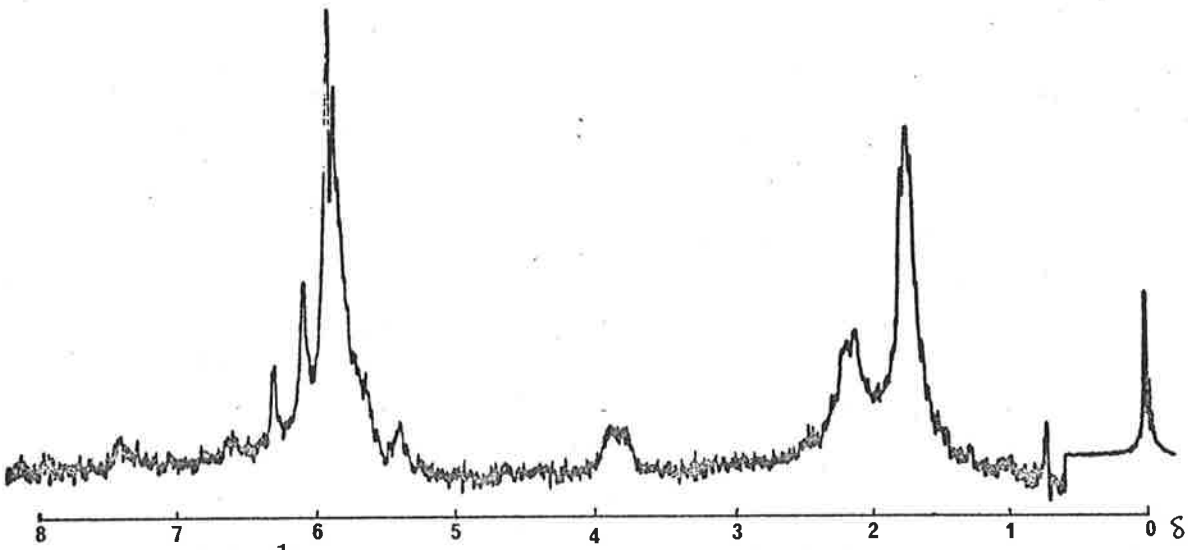


Fig. 3. 60MHz ^{1}H n.m.r. spectrum of bicyclo[6.4.0]dodeca-2,4,6,8,(9)-tetraene (58) obtained from solvolysis.

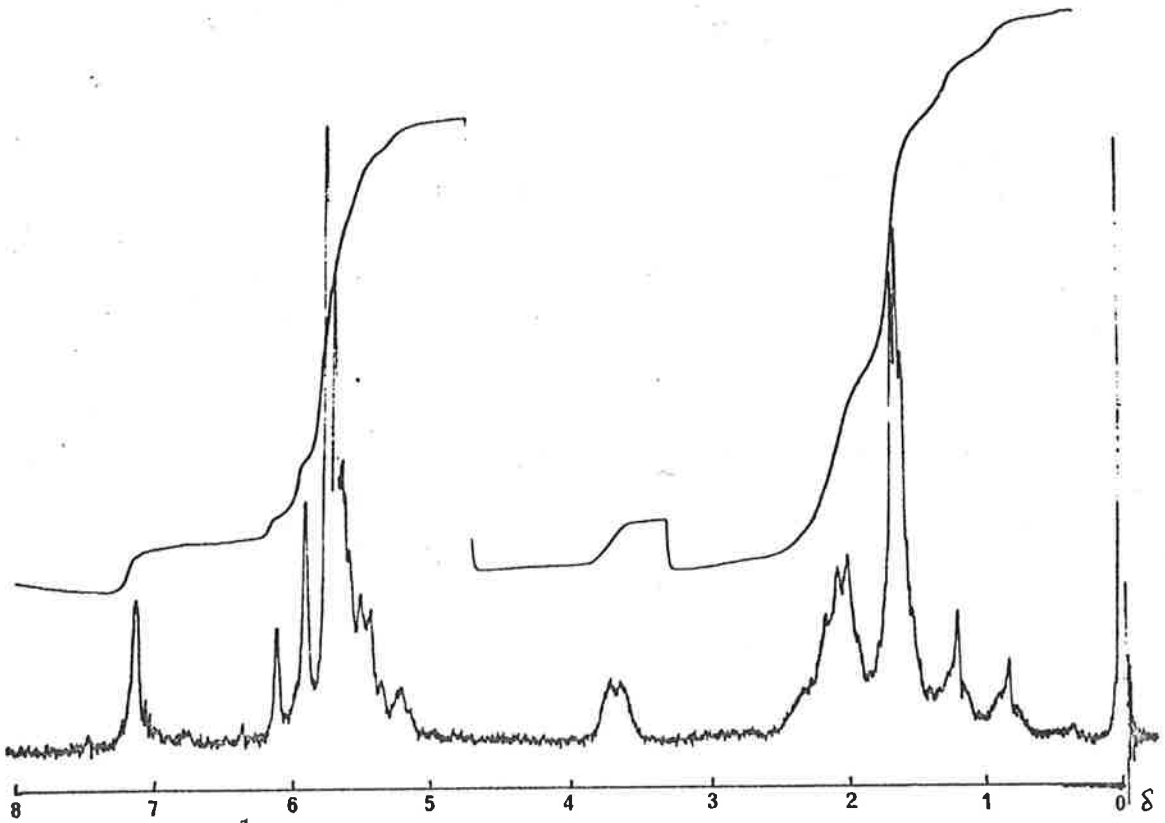


Fig. 4. 60MHz ^{1}H n.m.r. spectrum of bicyclo[6.4.0]dodeca-2,4,6,8,(9)-tetraene (58) obtained *via* Wittig reaction. The resonances at δ7.1 (triphenylphosphine) and 0.8-1.2 are impurities.

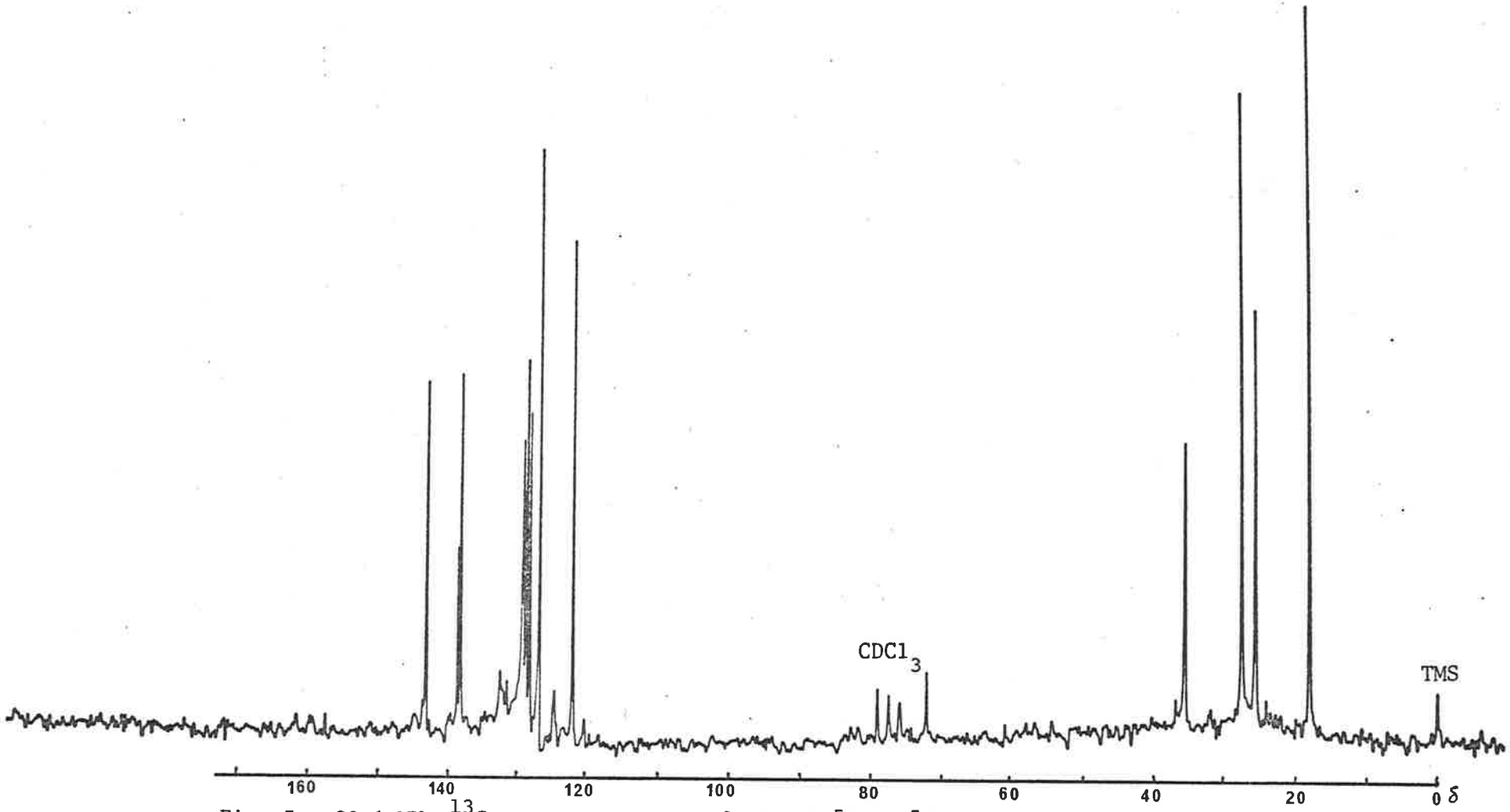


Fig. 5. 20.1 MHz ^{13}C n.m.r. spectrum of bicyclo[6.4.0]dodeca-2,4,6,8,(9)-tetraene (58).

the Wittig reaction with tetracyanoethylene gave a white solid in 24% yield (from the phosphonium salt). This solid was shown to be a mixture of 3 adducts; the ^{1}H n.m.r. spectrum of this mixture of adducts was identical to that of the adduct mixture obtained from the tetraene (58) prepared *via* solvolysis. Both of these adduct mixtures were shown (by high pressure liquid chromatography and ^{1}H and ^{13}C n.m.r. spectroscopy) to contain the same components in approximately the same proportion (see Chapter 7).

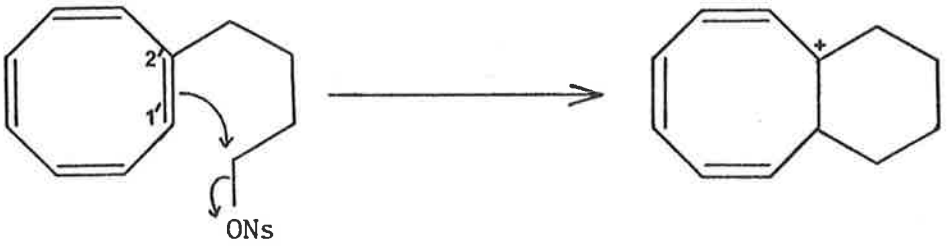
The tetraene (58), in common with the analogous tetraene (57), often polymerized upon concentrating solutions containing it and as a consequence care was taken to avoid concentration of its solutions whenever possible. The tetraene also underwent polymerization on standing in ether or low boiling petroleum, both at room temperature and at -15°. This fact is surprising in view of the relative stability of both (127) and (157) towards polymerization.[241]

6.4 Discussion

Both kinetic and product studies (Tables 15-17) show that extensive π-bond participation occurs during the solvolysis of 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) in buffered trifluoroethanol and buffered hexafluoropropan-2-ol. As expected, the extent of such participation (94% and 100% respectively) is much greater than that found for the acetolysis of (21) i.e. 43%:[53]

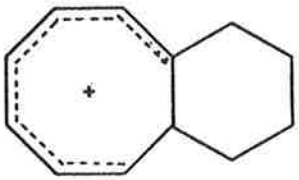
Gream and Mular have discussed the two possible pathways for π-bond participation during the acetolysis of (21).[53]

(i) One route (Scheme 7) involves participation by the 1',2'-double bond to give the ions (162) and/or (163) and/or (164).[53]



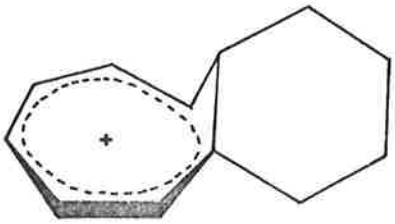
(21) (162)

and/or



(163)

and/or

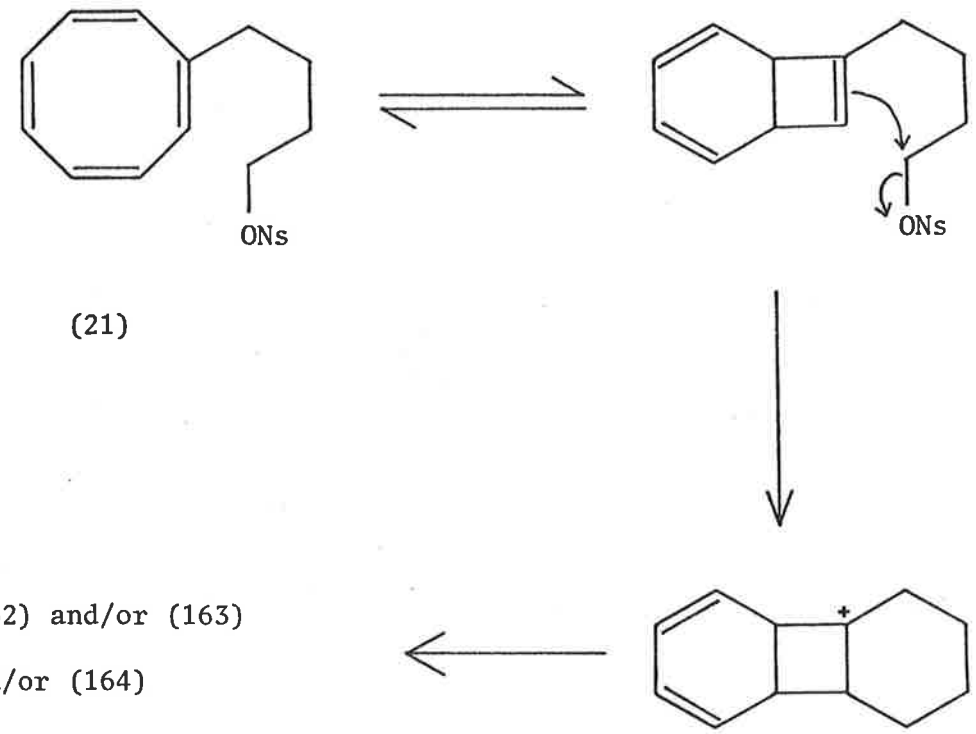


(164)

Scheme 7

(ii) The other route (Scheme 8) involves participation by the cyclobutene double bond of the tricyclic form of the ester (21) to give ions (165) and/or (162) and/or (163) and/or (164).[53] This was shown to be energetically feasible by the comparison of the free energy of activation for the valence isomerization of ethylcyclooctatetraene

(112 kJ mol^{-1} at 100°)[281] with the free energy of activation for the acetolysis of (21) at 100° i.e. 120 kJ mol^{-1}.[53]



(21)

(162) and/or (163) and/or (164)

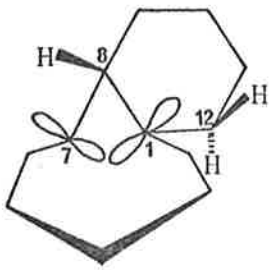
(165)

Scheme 8

Both the pathways proposed by Gream and Mular[53] for π-bond participation during the acetolysis of (21) appear to be valid for the solvolysis of (21) in trifluoroethanol and hexafluoropropan-2-ol; the free energy of activation at 100° for the solvolysis of (21) in these two solvents is 114 and 108 kJ mol^{-1}, respectively.

Gream and Mular[53] also rationalized the formation of (58) in preference to (157) by arguing that the counter-ion in ion-pairs abstracted the hydrogen β to the positive charge; it was shown that for ion-pairs of the ions (162), (163) and (164) the counter-ion would be more favourably placed to abstract a proton from C12 than from C8. Ion-pairs of the ion (165) were not considered by these workers as direct precursors to the products; the same argument, however, shows that the tetraene (58) would also be formed preferentially from ion-pairs of this ion (165).

Although the argument used by Gream and Mular to account for the preferential formation of (58) from π-bond participation during the acetolysis of (21) could also be applied to the solvolysis of (21) in trifluoroethanol and hexafluoropropan-2-ol, another argument involving stereo-electronic control may also be used.* Examination of models of the homotropylium ion (164) show that the flexibility of the 6-membered ring allows either of the C12—H bonds to attain planarity with the p orbital at C1 (166); the C8—H bond, however, is almost



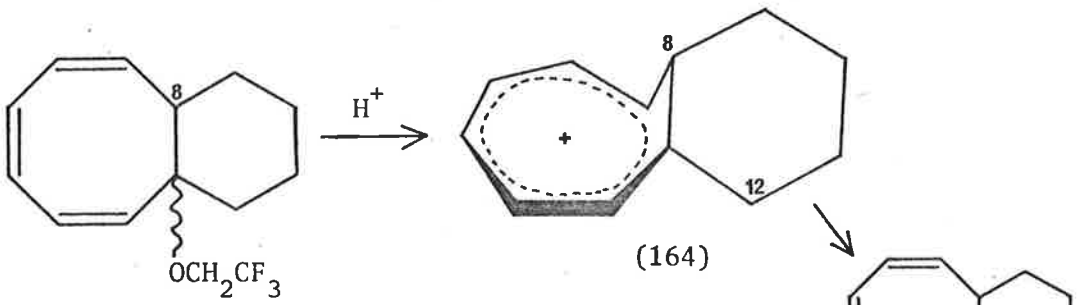
(166)

---

* See footnote p. 72.

perpendicular to this orbital (and the p orbital at C7). For the other possible intermediate ions i.e. (162), (163) and (165), the C8—H bond and one of the C12—H bonds are both nearly coplanar with the vacant p orbital and more equal mixtures of (58) and (157) would be expected from these ions.

The acid catalysed elimination of trifluoroethanol from the trifluoroethyl ethers (158) to give almost exclusively the tetraene with the exocyclic double bond (58) may also be explained by the intervention of a homotropylium ion intermediate. In this case an



(158) (164) (58)

ion-pair mechanism where the position of the counter-ion determines the products cannot be invoked because the leaving group leaves as a neutral molecule of low basicity i.e. trifluoroethanol.

The possibility that the olefin (58) is produced by elimination of trifluoroethanol (or hexafluoropropan-2-ol) from tertiary trifluoroethyl ethers (158) (or hexafluoroprop-2-yl ethers) during the solvolysis conditions cannot be dismissed.

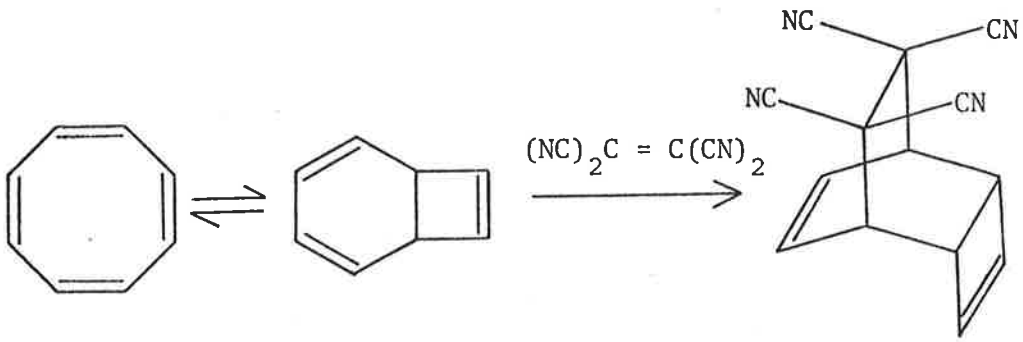
In summary, 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) solvolyses in trifluoroethanol and hexafluoropropan-2-ol with extensive π-bond participation. The formation of the tetraene (58) in preference to (157) may be rationalized by regiospecific β-H atom loss from a homotropylium ion intermediate or by the involvement of counter-ions in ion-pairs. The acid catalysed elimination of trifluoroethanol from (158) to give the same tetraene (58) may also be rationalized by the intervention of a homotropylium ion intermediate.

CHAPTER 7

Tetracyanoethylene adducts of bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene and bicyclo[6.4.0]dodeca-2,4,6,8(9)-tetraene

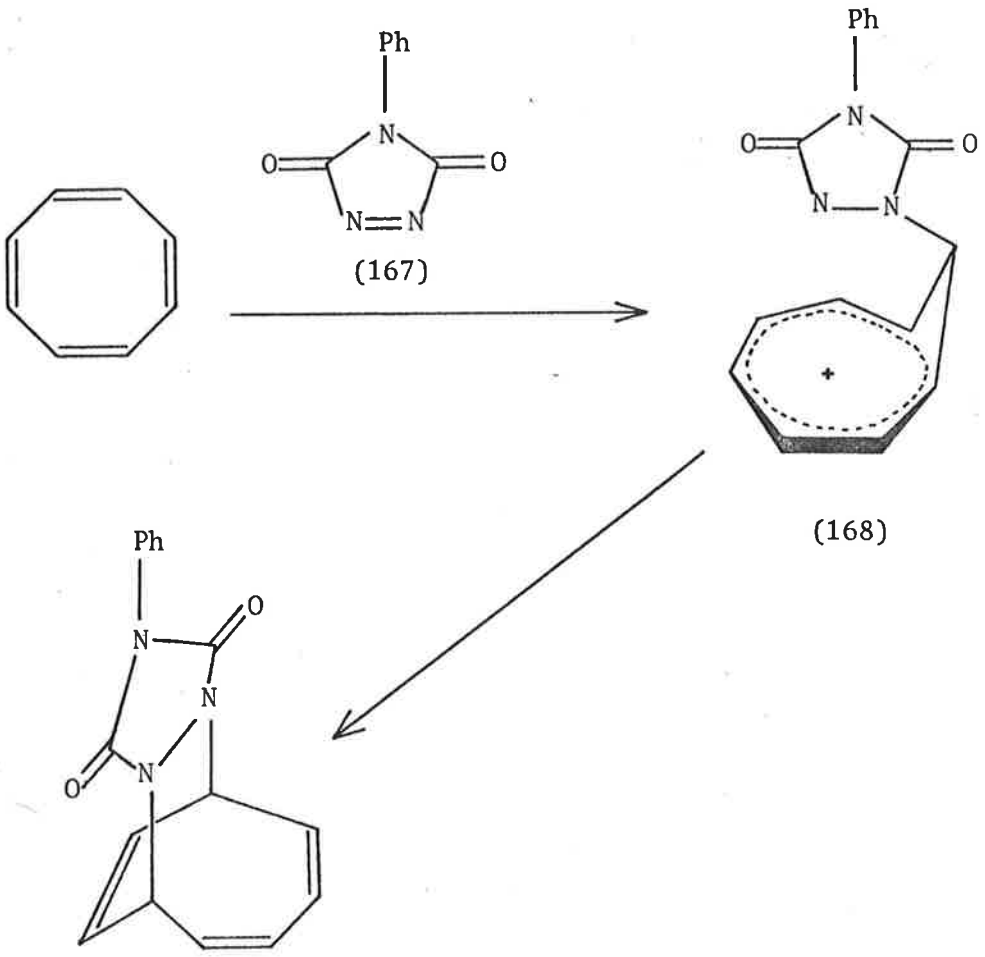
7.1 Introduction-reaction of cyclooctatetraene and derivatives with dienophiles

As the 'tub' shape of cyclooctatetraene precludes planarity and conjugation of the double bonds, 4+2 cycloaddition reactions with all but the most reactive dienophiles occur through the bicyclic tautomer of cyclooctatetraene.[246,247] Thus cyclooctatetraene, when treated with



(166)

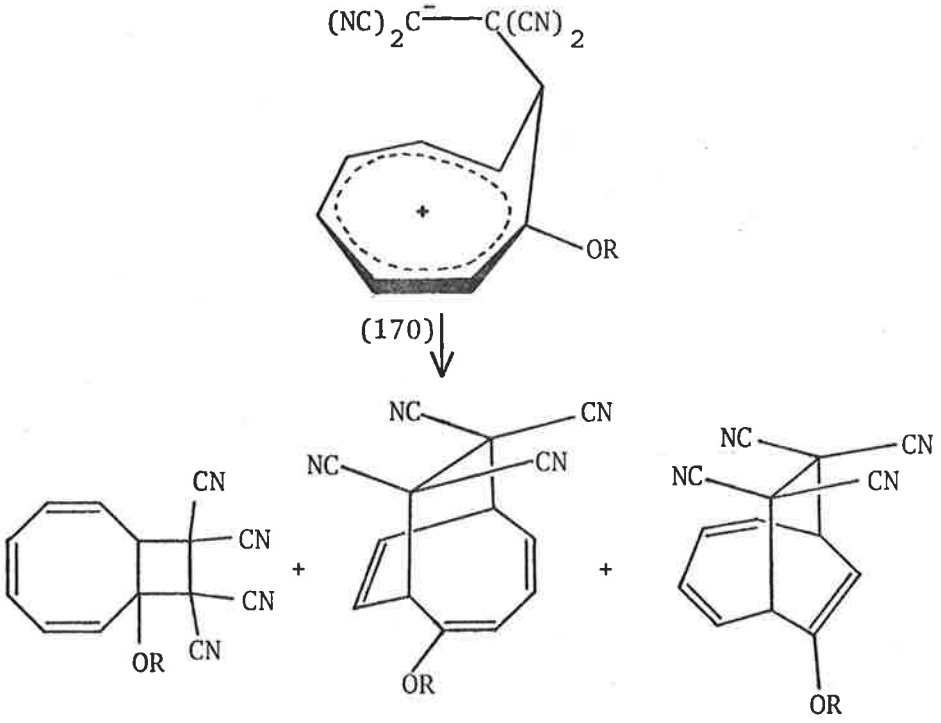
tetracyanoethylene gives the tricyclic adduct (166).[256] With very reactive dienophiles, such as 4-phenyl-1,2,4-triazoline-3,5-dione (167), 1,4 cycloaddition to the monocyclic tautomer of cyclooctatetraene is observed.[259,260,285,286] Such behaviour has been attributed to 4-phenyl-1,2,4-triazoline-3,5-dione (167) entering into a dipolar reaction with cyclooctatetraene to give the homotropylium zwitterion (168) which can undergo subsequent intramolecular charge annihilation to give (169).[260,286]



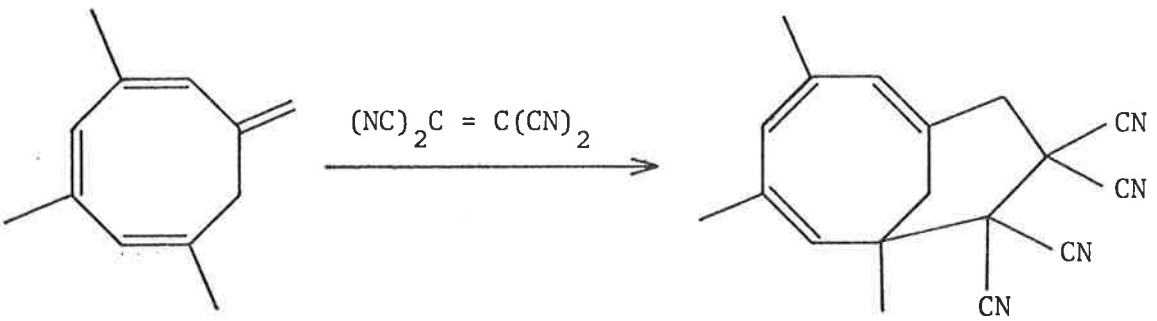
Although tetracyanoethylene adds to most cyclooctatetraenyl derivatives *via* the bicyclic tautomeric form, it adds to methoxy and phenoxycyclooctatetraene *via* the homotropylium zwitterion (170).[287] Charge annihilation may occur to give 1,2 and/or 1,4 addition products.*[287]

---

* Zwitterionic intermediates have also been observed for 2+2 cycloadditions of tetracyanoethylene to *trans* fixed 1,3-dienes[288] and enol ethers.[289]



Recently, Simons and Lagowski have reported the isolation of (171) from the treatment of a mixture of propyne oligomers with tetracyanoethylene;[290] the structure (171) was confirmed by X-ray crystallography.[290] It was proposed that (171) arose from the '8+2 cycloaddition' of



(172) (171)

tetracyanoethylene with 7-methylene-1,3,5-trimethylcycloocta-1,3,5-triene (172);[290] evidence for the presence of this tetraene (172) in the mixture of propyne oligomers could not be obtained, however.*[290]

7.2 The tetracyanoethylene adducts of bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57)

Treatment of a solution of the tetraene (57) in ethyl acetate with tetracyanoethylene followed by heating under reflux for 10 min. gave a white solid in 31% yield (from the sulphonate (29)**) after purification by preparative t.l.c. on silica gel. This product exhibited a sharp melting point and it was homogeneous by t.l.c.; the ^{13}C n.m.r. spectrum and the elemental analysis indicated that the adduct was pure. Spectral data indicates that the compound is 9,9,10,10-tetracyanotricyclo-[6.5.0.$0^{2,11}$]trideca-2,4,6-triene (173) and not the product expected for reaction *via* the tricyclic tautomer (174).

The ^{1}H n.m.r. spectrum of this adduct (Fig. 6) showed resonances for 5 olefinic hydrogen atoms (δ5.9-6.4), 3 allylic hydrogen atoms (3.82, 3.53 and 3.25, each integrating for 1 hydrogen) deshielded by the nitrile groups and 4 alicyclic hydrogen atoms (1.9-2.6) also deshielded by the nitrile groups. The resonances at 3.82 and 3.53 are

---

* Some aspects of this problem are presently being investigated by G.E. Gream and P. Kirkbride.

** If the yield of tetraene (57) from solvolysis is the same as that obtained for the analytical product studies (39%), then the yield for adduct formation is 79%. For preparative product studies, however, more concentrated solutions of the ester are used and the extent of polymerization is found to be greater. Consequently, the percentage yield for the formation of adduct (173) from the tetraene (57) is probably greater than 79%. The same yield was obtained for longer reaction times (3 hr.) in boiling ethyl acetate.

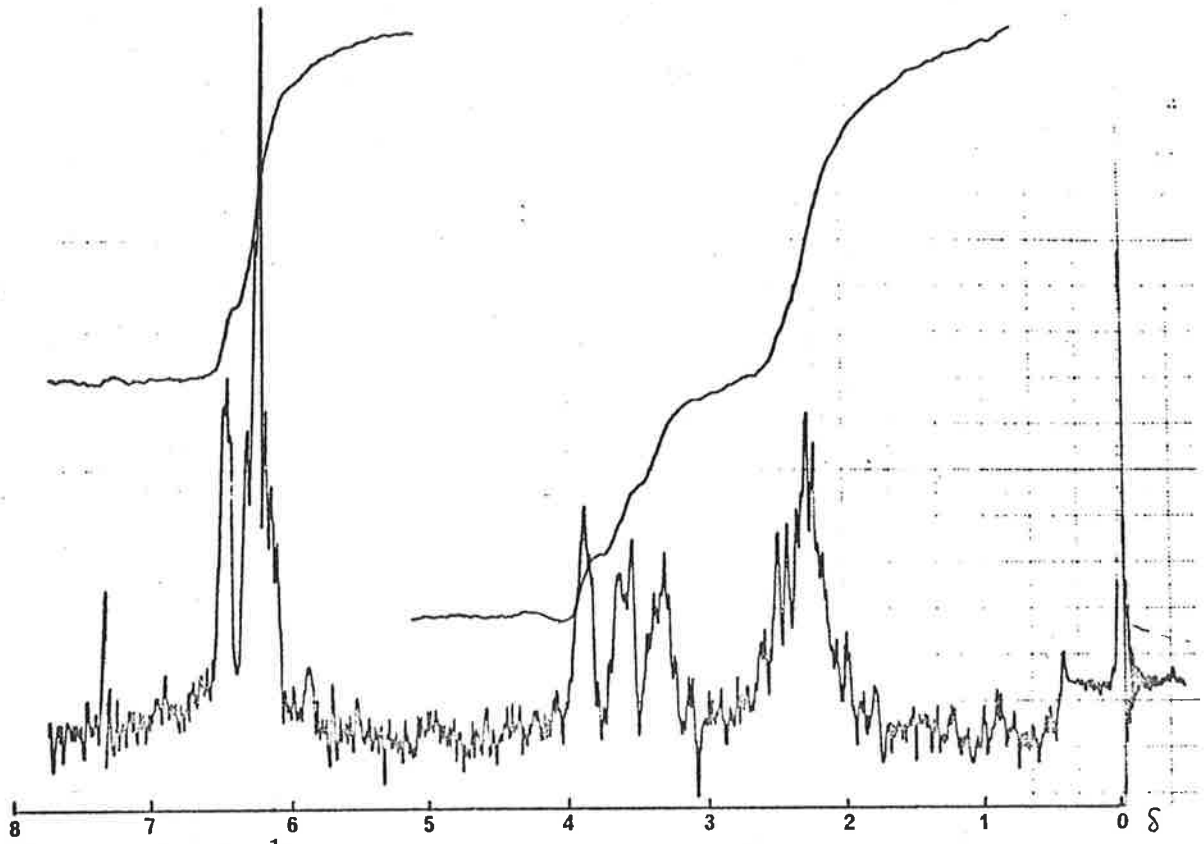
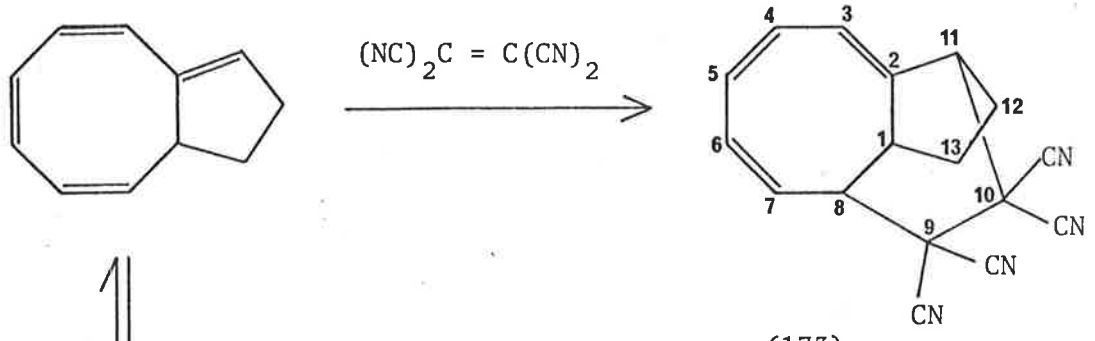
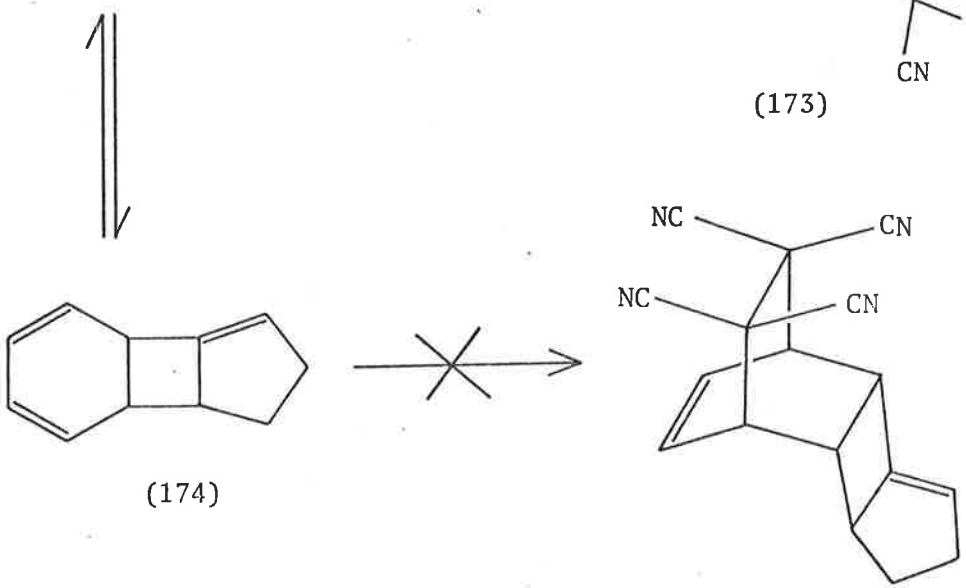


Fig. 6. 60 MHz ^{1}H n.m.r. spectrum of 9,9,10,10-tetracyanotricyclo-[6.5.0.$0^{2,11}$]trideca-2,4,6-triene (173) in $CDCl_3$.



(173)



(174)

assigned to H8 and H11* and the resonance at 3.25 is assigned to H1. The two hydrogen atoms closest to the nitrile groups (i.e. H8 and H11)* showed downfield shifts in the more polar solvent, d_6 acetone; in this solvent the H8 and H11 resonances were at 4.25 and 4.00.* The resonance for H1 did not show an appreciably solvent shift. The ^{13}C n.m.r. spectrum (Fig. 7) showed resonances for 6 olefinic carbon atoms (δ124-140) and 5 alicyclic carbon atoms (23-53).**

The ultraviolet spectrum of the adduct (173) (λ_{max}^{EtOH} 264 nm, ε 3,100) is very similar to that reported for cycloocta-1,3,5-triene (175) ($\lambda_{max}^{Cyclohexane}$ 265 nm, ε 3,600[291]).*** Models of the adduct

(175)

---

* Not necessarily respectively.

** For all of the adducts studied in this work, resonances that could be attributed to the nitrile carbons and the carbons bearing the nitrile groups were not detected.

*** The absorption maxima wavelength of (175) in ethanol is expected to be very similar to that in cyclohexane; the wavelength of absorption maxima for non-polar solutes are relatively unaffected by a change in solvent.[292]

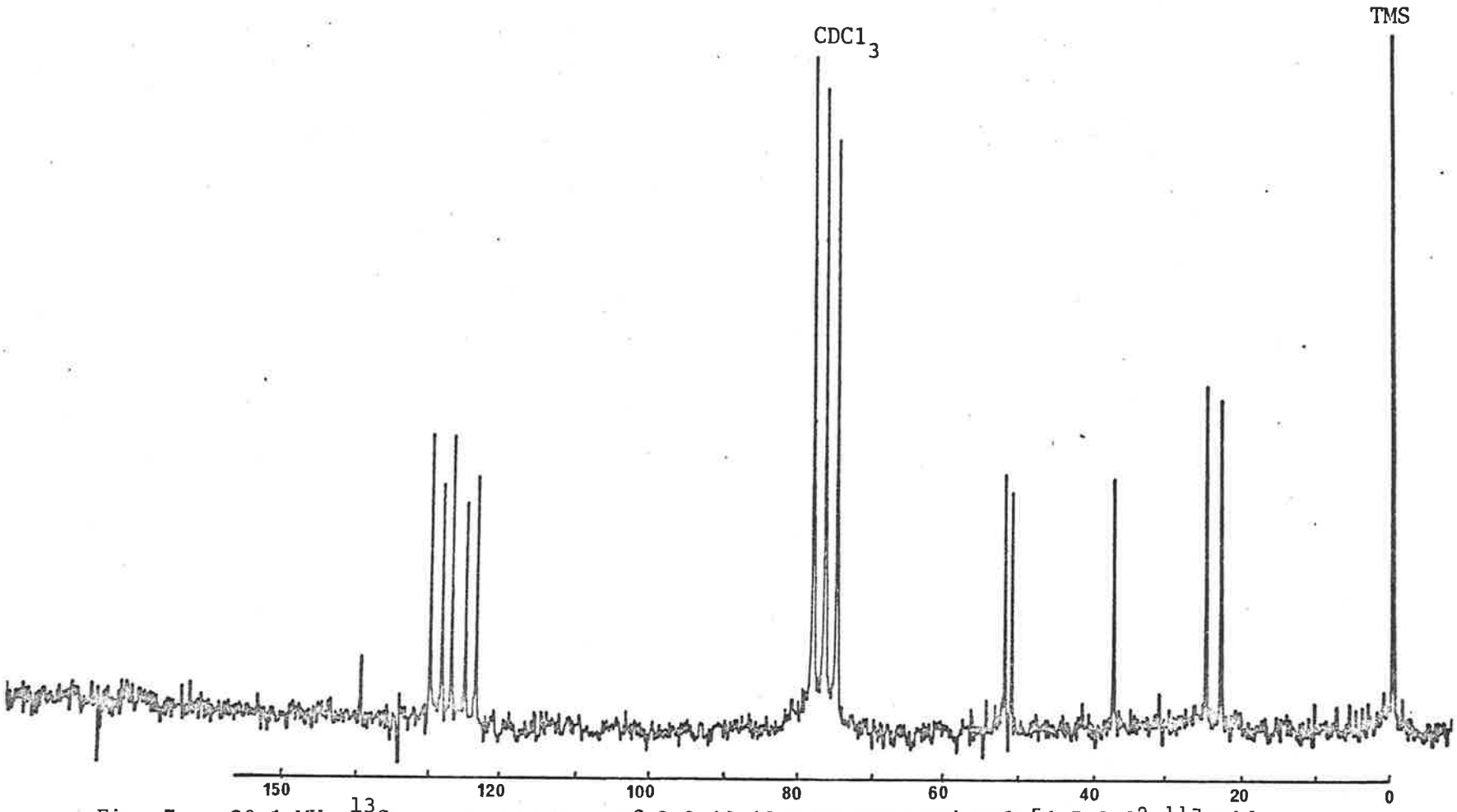


Fig. 7. 20.1 MHz ^{13}C n.m.r. spectrum of 9,9,10,10-tetracyanotricyclo[6.5.0.$0^{2,11}$]trideca-2,4,6-triene (173).

(173) and cycloocta-1,3,5-triene (175)[293] show that the geometry and extent of orbital overlap is very similar for the chromophores of both of these compounds.

7.3 The tetracyanoethylene adducts of bicyclo[6.4.0]dodeca-2,4,6,8(9)-tetraene (58).

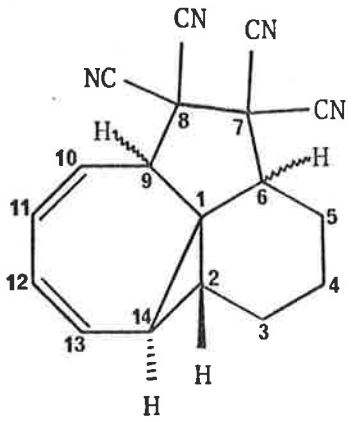
Treatment of the tetraene (58) with tetracyanoethylene gave a white solid in 97% yield [from the sulphonate (21)]. Both t.l.c. and ^{13}C n.m.r. spectroscopy indicated the presence of more than one compound. Preparative t.l.c. on silica gel did not give a separation; high pressure liquid chromatography (h.p.l.c.) using an absorbance detector at 280 nm indicated two peaks (ca. 3:2)* and preparative h.p.l.c. gave two fractions (3:2).* The fraction of longest retention time (smaller yield) was shown to be pure by ^{13}C n.m.r. spectroscopy; the other fraction was a mixture of two components. Comparison of the ^{1}H and ^{13}C n.m.r. spectra of the two fractions with that of the crude adduct mixture showed that there were no other components present in the crude adduct mixture.

Each of these fractions will be discussed in more detail.

(i) The compound of longest retention time by h.p.l.c. is tentatively identified as 7,7,8,8-tetracyanotetracyclo[7.5.0.0.^{1,6}0^{2,14}]-tetradeca-10,12-diene (176); four diastereoisomers are possible for this structure but the stereochemistry of the adduct has not been determined.

---

* Using the extinction coefficients of the separated materials and the area under each peak of the high pressure liquid chromatograph, the ratio of material in each fraction is calculated to be 1:1. The ratio of products obtained (3:2) is different from this calculated ratio because the peaks overlapped slightly and thus some material was not collected.



(176)

Evidence for this structure comes from the ^{1}H n.m.r. and ^{13}C n.m.r. and ultraviolet spectra.

The ^{1}H n.m.r. spectrum (Fig. 8a)* exhibits resonances for 4 olefinic hydrogen atoms; the spin-spin splitting pattern and the chemical shift values are consistent with the diene protons of structure (176). The doublet at δ3.93 (J 7.6 Hz, 1 hydrogen) is consistent with H9 which is both allylic and α to a cyclopropyl ring and also deshielded by the nitrile groups. Double resonance experiments (Figs. 8b and 8c) showed conclusively that this proton was coupled to an olefinic hydrogen atom. The resonances assigned to H9 and H6 (in deuterochloroform, δ3.93 and 2.57, respectively) showed an appreciable downfield shift in the more polar solvent, d_3 acetonitrile i.e. δ4.10 and 2.75 respectively; these two protons are those nearest to the nitrile groups. The other

---

* The spectra in Fig. 8 were recorded in d_3 acetonitrile. The chemical shifts reported here were obtained in deuterochloroform.

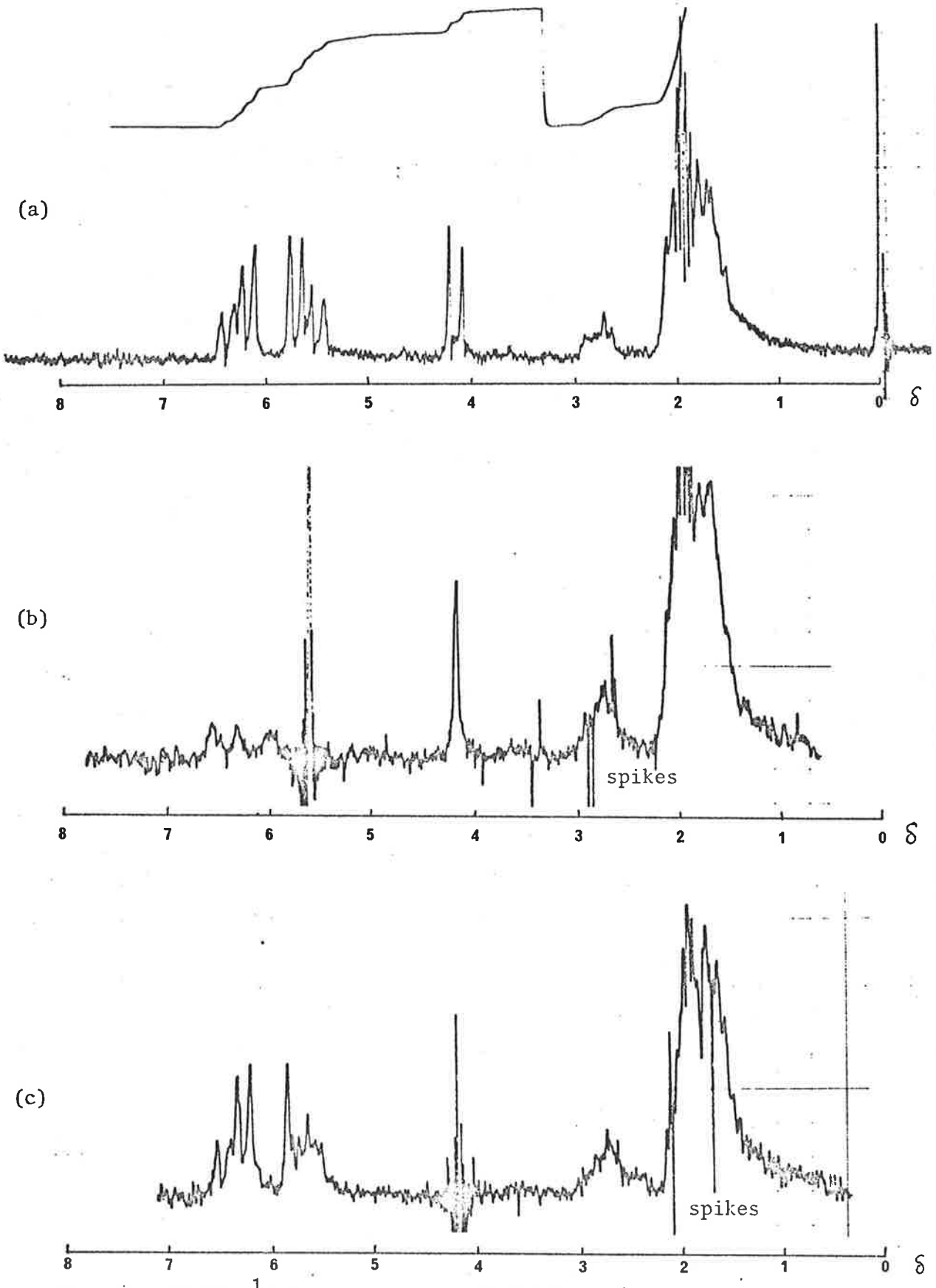


Fig. 8. 60 MHz ^{1}H n.m.r. spectra of (176) in d_3 acetonitrile. Some of the resonances at δ1.9 can be attributed to incompletely deuterated solvent. Double resonance experiments: (b) irradiation at δ5.6, (c) irradiation at δ4.15.

resonances did not show a significant solvent shift.

The ^{13}C broadband decoupled and off resonance decoupled n.m.r. spectra (Fig. 9) were also consistent with the structure (176); 4 olefinic carbon resonances were present and all of these were each bonded to only one hydrogen atom. The region between δ20 and 60 contained resonances for 8 carbon atoms; four of these (δ59.33, 52.96, 27.69, 26.96) were each bonded to only one hydrogen atom and one was quaternary (δ49.31). The remaining three carbon atoms (δ20.3-20.7) were each bonded to two hydrogen atoms. Further evidence for the structure (176) was obtained from the fully coupled ^{13}C n.m.r. spectrum; the $^{13}C—^{1}H$ coupling constant for the olefinic carbons was 163±5 Hz whilst the resonances at δ59.33, 52.96 and 20.3-20.7 had $^{13}C—^{1}H$ coupling constants typical of medium ring alicyclic carbons i.e. 125±5 Hz. The resonances at δ27.69 and 26.96, however, exhibited $^{13}C—^{1}H$ coupling constants of 175±5 Hz; the magnitude of these coupling constants[294] combined with the relatively low chemical shift (for tertiary carbon atoms) is strong evidence for a cyclopropyl ring in structure (176).

The ultraviolet absorption of (176) (λ_{max}^{EtOH} 280 nm, Table 18) suggests that there is more conjugation present in (176) than for a simple 1,3-diene such as cyclohexa-1,3-diene (177) (λ_{max}^{EtOH} 256) or cyclohepta-1,3-diene (178) (λ_{max} 248). Since the n.m.r. data show that there are only two double bonds, the presence of a cyclopropyl group extending the conjugation is suggested. It is known that conjugation of a chromophore with a cyclopropyl group shifts the absorption maxima to a longer wavelength;[302] this shift however is usually less than that for a double bond extending the conjugation.

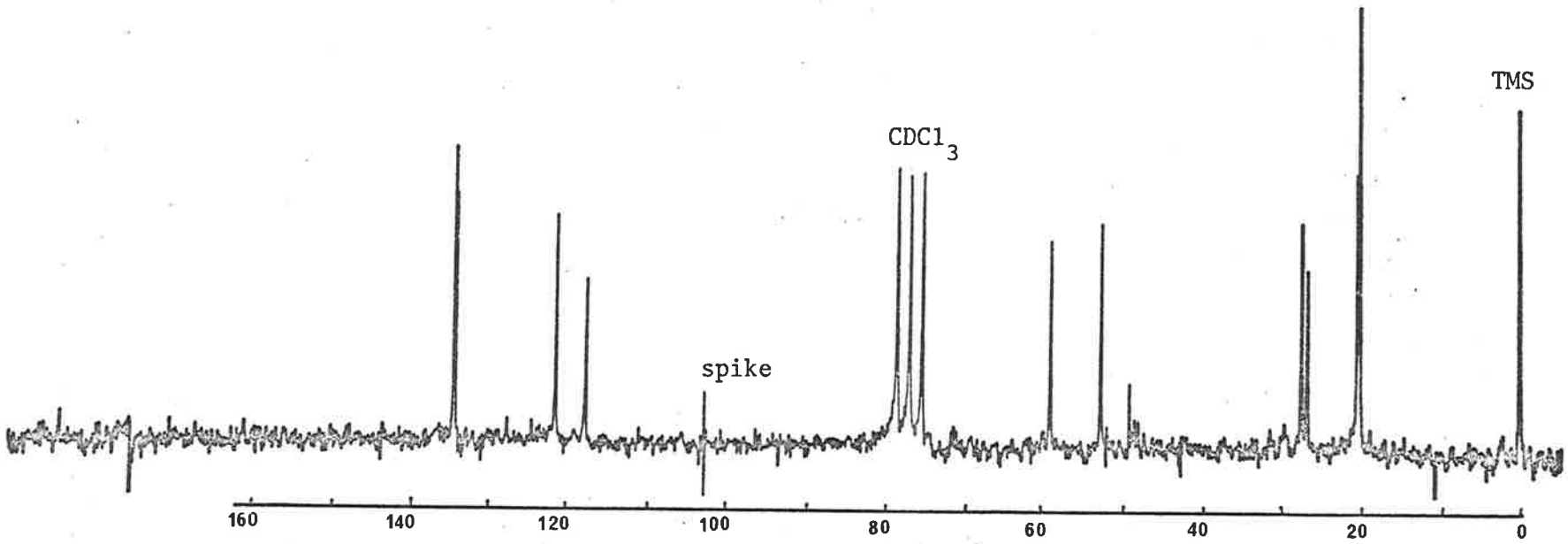
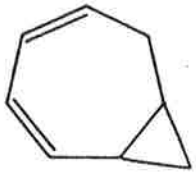


Fig. 9. 20.1 MHz ^{13}C n.m.r. spectrum of 7,7,8,8-tetracyanotetracyclo[7.5.0.$0^{1,6}0^{2,14}$]tetradeca-10,12-diene (176).

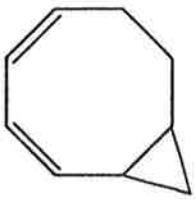
(177)

(178)



(179)

(180)



(181)

Substrate	Solvent	λ_{max} (nm)	ε_{max}	Reference
(176)	ethanol	280	4,000	
(177)	ethanol	256	7,900	295
(178)	*iso*-octane	248	7,500	296
(179)	ethanol	258	4,200	297
	ethanol	263		298
(180)	cyclohexane	228	5,600	299
(181)	ethanol	234	5,600	300
	ethanol	234	6,460	301

Table 18. Ultraviolet absorption data for (176) and some model compounds.

Of the compounds in Table 18, the one that resembles structure (176) most closely is bicyclo[5.1.0]octa-2,4-diene (179) (λ_{max} ca. 260); the wavelength difference between the absorption maximum for this compound and that of (176) may be explained, at least in part, by the greater alkyl substitution present in the latter. A further possible explanation might lie in the slightly different geometries and extents of orbital overlap for the chromophore in each molecule. That this factor greatly affects the absorption maximum wavelength can be seen by comparing the absorption maxima for bicyclo[5.1.0]octa-2,4-diene (179) with bicyclo[6.1.0]nona-2,4-diene (181) (Table 18); a further example is afforded by the comparison of cyclohexa-1,3-diene (177) cyclohepta-1,3-diene (178) and cycloocta-1,3-diene (180) (Table 18). Models show that (179) and the four diastereoisomers of (176) all have very similar (but not necessarily identical) chromophore geometries and similar amounts of orbital overlap.

(ii) The second fraction (shorter retention time) obtained by h.p.l.c. from the mixture of tetracyanoethylene adducts of the tetraene (58) was shown to be a mixture; although it appeared as only one peak by h.p.l.c., ^{13}C n.m.r. spectroscopy showed that two compounds (ca. 80:20)* were present. Elemental analysis and spectral data suggest that both components are tetracyanoethylene adducts of (58).

The major component of the mixture is tentatively identified as 9,9,10,10-tetracyanotricyclo[6.6.0.$0^{2,11}$]tetradeca-2,4,6-triene (182). In the ^{1}H n.m.r. spectrum of this mixture, (Fig. 10) the following

---

* This ratio was determined from the ^{13}C n.m.r. spectrum. In view of the lack of a direct relationship between the intensity or integral of ^{13}C resonances and the amount of those carbon atoms present,[303,304] this ratio (i.e. 80:20) must be considered to be very approximate.

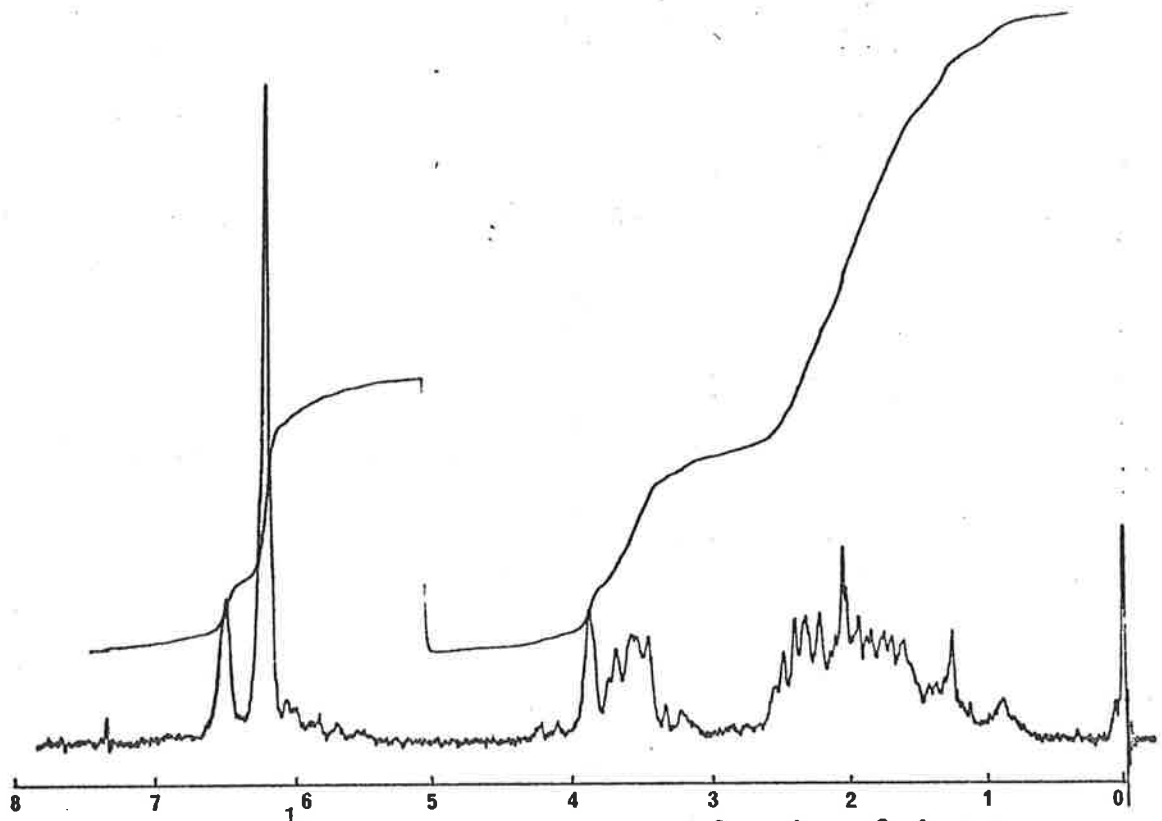
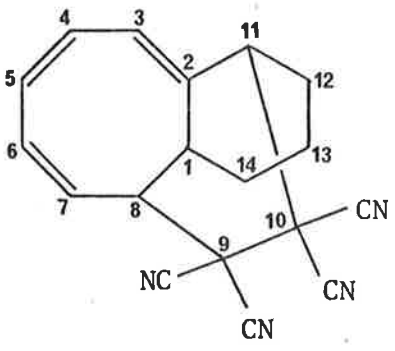


Fig. 10. 60 MHz ^{1}H n.m.r. spectrum of the fraction of shorter retention time by h.p.l.c. from the mixture of tetracyanoethylene adducts of tetraene (58).



(182)

resonances could be attributed to structure (182): δ6.0-6.5 (5H, olefinic), 3.3-3.9 (3H, allylic hydrogens, deshielded by the nitrile groups) and 1.0-2.6 (6H, alicyclic). The resonances of lower intensity (δ5.3-6.0, 4.1, 3.1 and 0.8- ca. 1.4) are presumably due to the minor component. The ^{13}C n.m.r. spectrum (Fig. 11) is complicated by the presence of the minor component. Of the more intense resonances, the 6 resonances between δ18 and 52 are consistent with the 6 alicyclic carbon atoms of (182).* The assignment of the olefinic carbon resonances, however, is more difficult. The structure (182) requires 6 olefinic carbon resonances; one of these is quaternary and is expected to give rise to a weak resonance at higher chemical shift than the other 5.**[304] The resonance at 135.1 ppm is thus assigned to C2; only 4 resonances of high intensity are present in the region δ120-130, but one is of higher intensity than the others and probably represents resonances for two carbon atoms. The remaining resonances of lower intensity (4 olefinic and 8 saturated carbon atoms) are attributed to the minor component.

The ultraviolet spectrum of the above mixture (the fraction of lower retention time by h.p.l.c.) (λ_{max}^{EtOH} 265 nm, ε 3,400) is very similar to that of the similar adduct (173) (λ_{max}^{EtOH} 264 nm, ε 3,100) and to cycloocta-1,3,5-triene (175) ($\lambda_{max}^{cyclohexane}$ 265 nm, ε 3,600[291]); models show that the chromophore of all three of these trienes has a similar geometry and similar extent of orbital overlap. Thus the ultraviolet spectrum of this mixture is consistent with the structure (182); in view of the known impurity present in this sample, however, this result

---

* See second footnote, p. 128.

** This was observed for the analogous adduct (173) (Fig. 7).

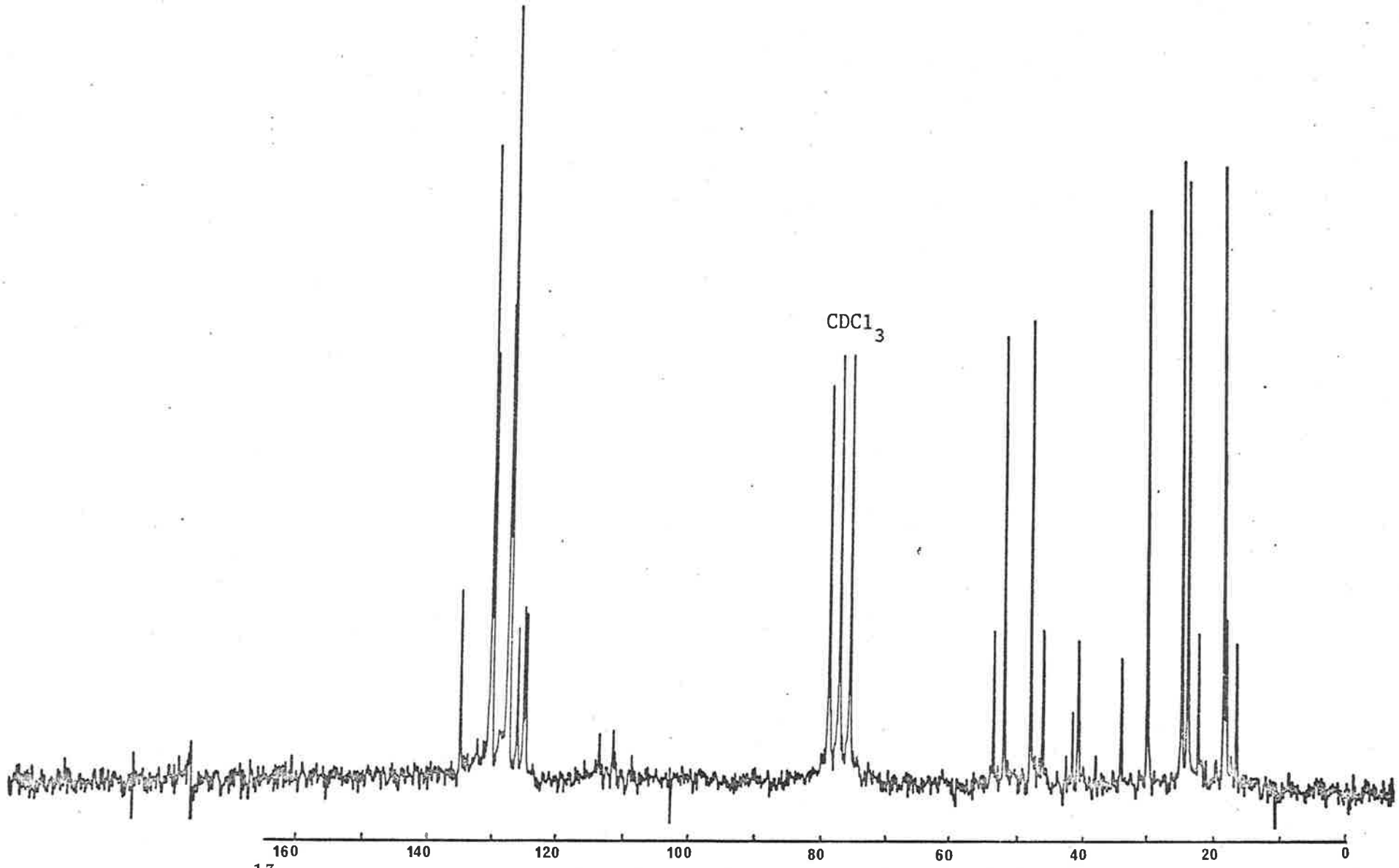
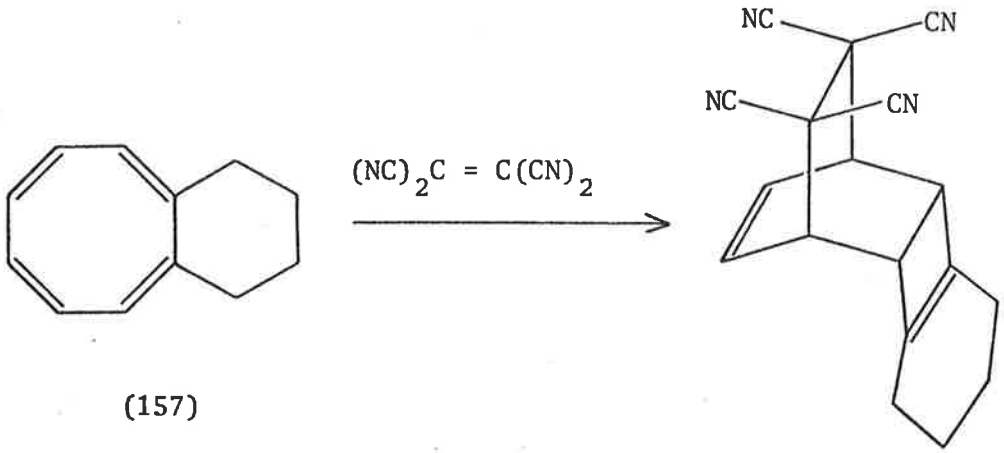


Fig. 11. 20.1 MHz ^{13}C n.m.r. spectrum of the fraction of shorter retention time by h.p.l.c. from the mixture of tetracyanoethylene adducts of tetraene (58).

must be interpreted with caution.

The minor component in the above mixture had different ^{13}C n.m.r. absorptions to those of the tetracyanoethylene adduct of bicyclo[6.4.0]-dodeca-1,3,5,7-tetraene (157) i.e. (183); this adduct was synthesised



(157)

(183)

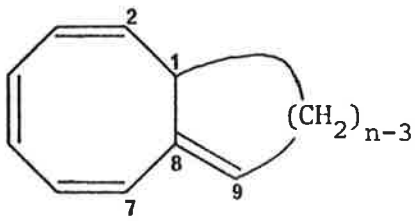
from an authentic sample of (157).

The same three adducts (i.e. those tentatively identified as (176) and (182) and the unidentified adduct) were obtained in the same proportion from the tetraene (58) whether (58) was prepared *via* the Wittig reaction or by solvolysis.

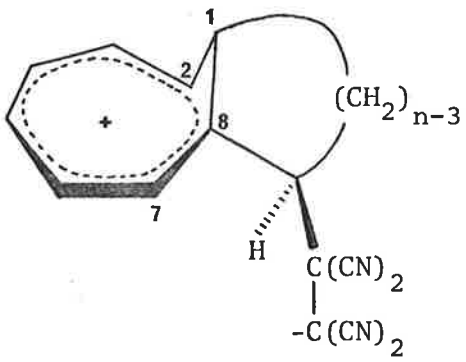
7.4 Discussion

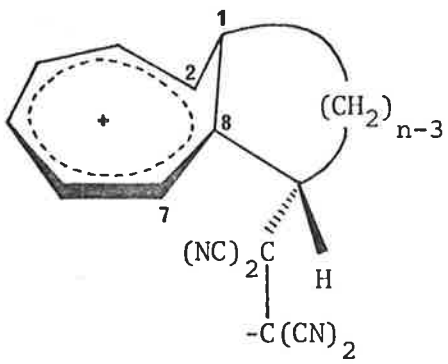
Two methanisms for the formation of tetracyanoethylene adducts from the tetraenes (57) and (58) can be considered.

(i) A stepwise mechanism: the addition of tetracyanoethylene to (57) and (58) may occur *via* homotropylium zwitterionic intermediates [(184)-(187)] in which both positive and negative charges are stabilized



n = 5 (57)
n = 6 (58)



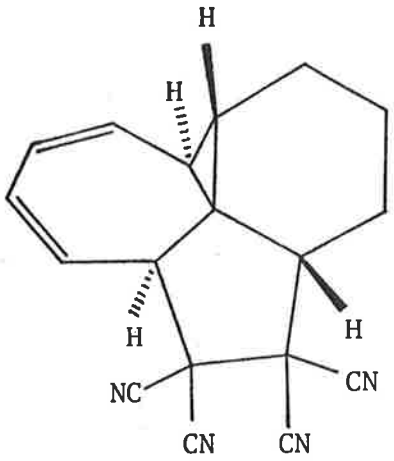


n = 5 (184)
n = 6 (185)

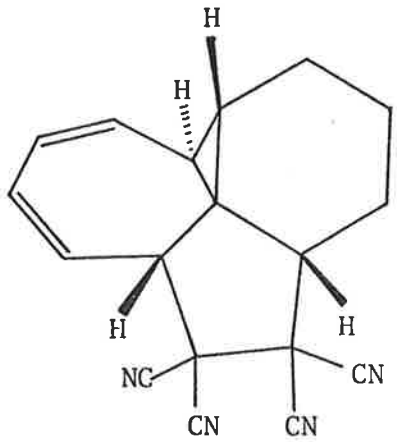
(186)
(187)

by delocalization. Although charge annihilation could conceivably take place at any of the seven sp^2 centres of the homotropylium ion in (184)-(187), examination of models shows that for (186) and (187) charge annihilation at only C2, C7 or C8 may take place without introducing excessive strain energy; for both (186) and (187), charge annihilation at C2 to give (173) and (182), respectively, both of which are observed

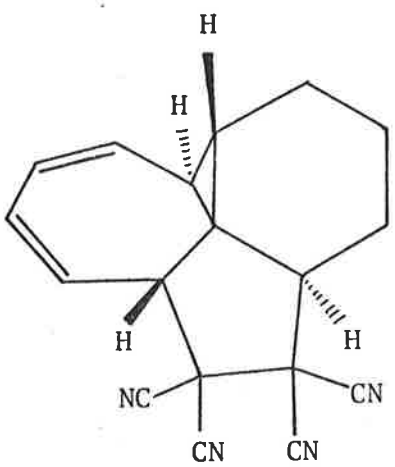
products, involves the least strain. For (184) and (185), charge annihilation at C7 and C8 appear to be relatively strain free.



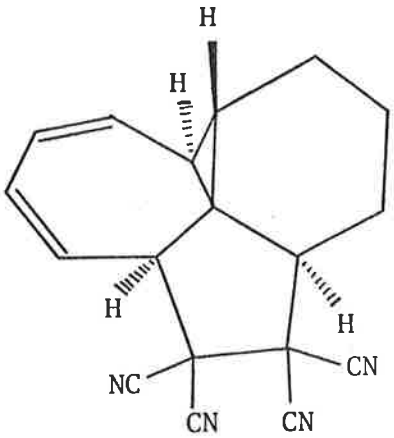
(188)



(189)



(190)



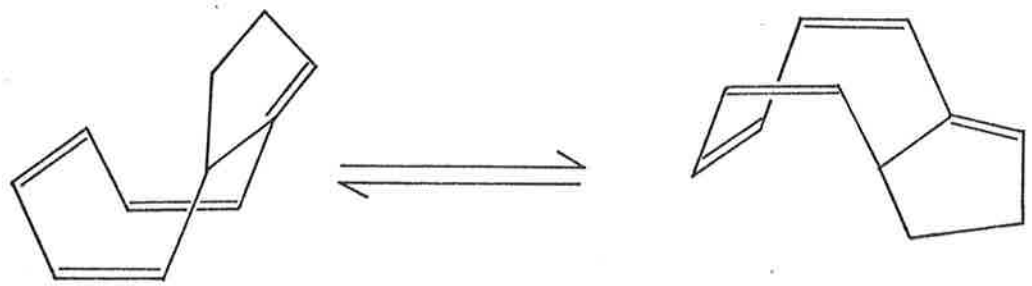
(191)

For (187), charge annihilation at C7 could conceivably give rise to both of the diastereoisomers (188) and (189); models show, however, that the formation of (188) from (187) is most unlikely in view of the excessive strain energy that would be introduced in attaining the required transition state. The zwitterion (185) could give rise to either

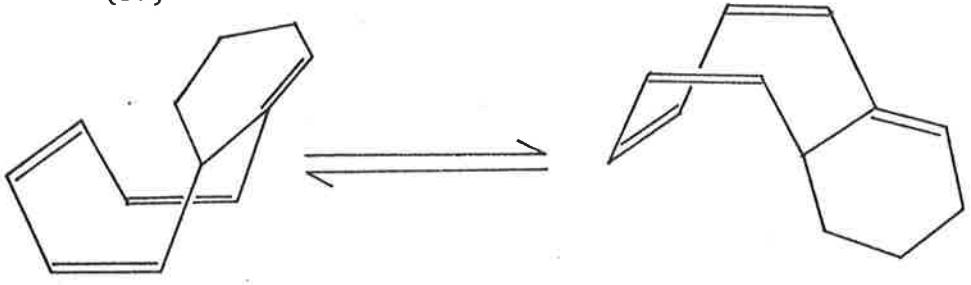
(190) or (191) by charge annihilation at C7.

The fact that the addition of tetracyanoethylene to (57) gives only one product i.e. (173), implies that the addition to the 8,9-double bond of that tetraene occurs stereospecifically to give (186). For the homologue (58) stereospecific addition of tetracyanoethylene might also occur; if this is the case, the greater conformational mobility of the 6-membered ring of (187) compared to the 5-membered ring of (186) may account for the formation of 3 products in this case.

(ii) An alternative mechanism which might be invoked to account for the formation of (173) and (182) from the treatment of (57) and (58), respectively, with tetracyanoethylene is a concerted 8+2 cycloaddition (thermally allowed by the Woodward Hoffman rules). It should be noted, however, that models show that the 8-membered ring of both (57) and (58) is 'tub' shaped (equations 12 and 13) and thus the extent of π-orbital overlap would be small. Furthermore, this mechanism does not account for the formation of (176).



(57) (12)



(58) (13)

EXPERIMENTAL SECTION

General

Melting points were determined either in Pyrex capillaries using an electrically heated Gallenkamp apparatus (for some of the work described in chapter 1 only) or by means of a Kofler hot-stage microscope and are uncorrected.

Infrared spectra were determined in Nujol mulls for solids and as liquid films for liquids unless otherwise stated. The spectra were recorded on either a Jasco IRA-1 or a Unicam SP200G grating spectrometers. The absorption maxima (ν_{max}) are recorded in cm^{-1} and the intensities of the absorptions are expressed as follows: s, strong; m, medium; w, weak; b, broad.

Ultraviolet spectra were recorded in ethanol solution on either a Unicam SP800 or SP8-100 spectrophotometer.

^{1}H Nuclear magnetic resonance (n.m.r.) spectra were determined in carbon tetrachloride solution (unless otherwise stated) containing tetramethylsilane as internal standard; spectra were recorded at 60MHz (unless otherwise stated) with either a Varian T60 or Jeol JNM-PMX60 spectrometers. 80MHz Fourier transform spectra were recorded with a Brüker WP-80 spectrometer.

^{13}C N.m.r. spectra were recorded in deuterochloroform solution (unless otherwise stated) containing tetramethylsilane as internal standard with a Brüker WP-80 spectrometer operating at 20.1MHz. Where obtained, the multiplicity of the off resonance decoupled spectrum is given in brackets; $^{13}C - {}^{1}H$ coupling constants were obtained from the fully coupled ^{13}C n.m.r. spectrum.

Mass spectra were determined with an Hitachi Perkin-Elmer RMU-7D spectrometer operating at 70eV or an AEI-GEC MS 3074 high resolution mass spectrometer; accurate mass measurements were obtained by the use of the latter instrument.

The gas-liquid chromatography (g.l.c.)-mass spectra were determined either with a Perkin-Elmer F11 gas chromatograph connected to an AEI MS 30 mass spectrometer at Flinders University, Bedford Park or the AEI-GEC MS 3074 high resolution mass spectrometer and associated Pye-Unicam 104 gas chromatograph.

Analytical g.l.c. was carried out with either Perkin-Elmer 800, 881, 990 or Pye Unicam 104 gas chromatographs. Quantitative work was carried out on the Perkin-Elmer 881 gas chromatograph connected to a Perkin-Elmer 194B printing integrator. Preparative g.l.c. was carried out on either Varian A-700, A-705 Autopreps or Pye 104 gas chromatographs. All gas chromatographs were equipped with flame ionization detectors. The following columns were used:

A. 7.5% Phenyldiethanolamine succinate (PDEAS) on Chromosorb W (80-100 mesh) which had been washed with aqueous sodium hydroxide, 2m × 2mm.

B. 7.5% PDEAS on sodium hydroxide washed Chromosorb W (80-100), 3.6m × 2mm.

C. 5% Apiezon M on Varaport 30 (100-120), 3.6m × 2mm.

D. 10% Carbowax 20M on sodium hydroxide washed Chromosorb W (80-100), 3.6m × 2mm.

E. 5% UCON on Varaport 30 (100-120), 3.6m × 2mm.

F. 15% DEGS on Chromosorb W (80-100), 6m × 2mm.

G. 2.5% Carbowax 20M on Varaport 30 (100-120), 2.5m × 2mm.

H. 7.5% PDEAS on sodium hydroxide washed Chromosorb W (80-100), 2m × 5mm.

I. 5% Carbowax 20M TPA on Varaport 30 (100-120), 2.2m × 3mm.

J. 20% Apiezon M on Chromosorb A (45-60), 1.5m × 6.5mm.

K. 7.5% PDEAS on sodium hydroxide washed Chromosorb W (80-100), 2.6m × 3.5mm.

L. 15% FFAP on sodium hydroxide washed Chromosorb A (40-60), 2.4m × 6.5mm.

Columns A and F were made of stainless steel; all other columns were of Pyrex glass. For columns B, C, D, E, F, G and I, the flow rate of carrier gas (nitrogen) was 28ml/min. and for columns H, J, K and L, 60-100ml/min. When columns A and H were used for g.l.c.-mass spectra determinations the flow rate of carrier gas (helium) was 40ml/min.

In this text, light petroleum refers to the fraction of b.p. 55-65°, while low boiling petroleum refers to the fraction of b.p. 30-40°. All organic solvent extracts were dried over anhydrous potassium carbonate unless otherwise stated.

Microanalyses were performed by the Australian Microanalytical Service, Melbourne.

Kinetic determinations

(i) Purification of materials

"Super dry" ethanol was obtained by the method described[305] and stored over 3A° molecular sieves.

Trifluoroethanol was stirred and heated under reflux over a mixture of anhydrous calcium sulphate and anhydrous potassium carbonate for 2 hr. and then distilled through a fractionating column;[160] the fraction b.p. 73-74° was collected and stored over 3A° molecular sieves.

Hexafluoropropan-2-ol was heated under reflux over anhydrous calcium sulphate for 2 hr. and then distilled through a fractionating column. The fraction b.p. 57-58° was collected and stored over 4A° molecular sieves.

Triethylamine was allowed to stand over sodium hydroxide pellets for 16 hr., filtered and then distilled from ca. 2% napthyl isocyanate.[306]

Acetic acid (analytical reagent grade) was distilled through a fractionating column from acetic anhydride. Acetic anhydride (1%) was added to the distillate.

(ii) Method A

Rate constants were determined by the ampoule technique. A solution (0.0025M, 25ml) of the *p*-nitrobenzenesulphonate in the appropriate solvent containing 0.01M triethylamine was prepared.* The

---

*For solvolyses in ethanol buffered with sodium ethoxide, 0.016M sodium ethoxide in ethanol was used; for these solvolyses the solutions were initially 0.01M in ester. In order to determine the absorption values for solvolyses in ethanol buffered with sodium ethoxide, the solutions were diluted with ethanol to give 100ml of solution instead of the usual 25ml.

solution was transferred to a burette and aliquots (ca. 2.0ml) were sealed in twelve ampoules under nitrogen and immersed at the one time in a constant temperature bath (±0.05°). After thermal equilibrium had been established (10-15 min.), the first ampoule was removed from the bath and placed in an ice bath (dry-ice ethanol for fast reactions) to quench the reaction. The time of removal of this ampoule was taken as "zero" time. The remaining ampoules were removed after the appropriate intervals of time. Each ampoule was opened and an aliquot (ca. 1.7ml, withdrawn with a constant volume pipette) of the solution was placed in a volumetric flask and redistilled ethanol was added to give 25ml of solution. The absorbance at 280nm was determined for each solution. The first order rate constants were determined by measuring the slope (by the method of least squares) of plots of $\log_e[(A_t - A_\infty)/(A_o - A_\infty)]$ against time, where A_t is the value of the absorbance for time t, A_∞ is the value of the infinity absorbance (i.e. at ca. 10 half lives), and A_o is the value of the absorbance at "zero time".

Rate constants were found to be the same (within experimental error) to those obtained from other wavelengths in the range 225-300nm. The greatest difference between the "zero" and "infinity" absorbance occurs at ca. 280nm.

Activation parameters were determined on a CDC 6400 computer by use of QCPE Program No. 79.

(iii) Method B

Quartz ultraviolet cells with tight fitting teflon stoppers were allowed to equilibrate thermally in the thermostatted block of Unicam SP800 ultraviolet spectrophotometer. A 0.0002M solution of the

appropriate *p*-nitrobenzenesulphonate ester was quickly prepared using trifluoroethanol (containing 0.0008M triethylamine) which had been thermally equilibrated at the appropriate temperature for 1 hr. before use. The cell was rinsed several times with the solution before being filled and then placed in the thermostatted block of the spectrophotometer. The reference cell was filled with trifluoroethanol (containing 0.0008M triethylamine) which also had been equilibrated at the same temperature. After thermal equilibration (10-15 mins.) the absorbance at 280nm was recorded. This was taken as "zero" time. At regular intervals thereafter, the absorbance was recorded at 280nm until ca. 3 half lives had elapsed; after 10 half lives the "infinity" absorbance was recorded. The rate constants were determined from the absorbance values in the same manner as described above.

(iv) Method C

A solution (ca. 0.01M, 50.0ml) of the required *p*-nitrobenzene-sulphonate in the appropriate solvent buffered with triethylamine (0.02M) was prepared in a 50ml volumetric flask. The solution was transferred to a burette and aliquots (ca. 5.5ml) were sealed in nine ampoules under nitrogen and immersed at the one time in a constant temperature bath. After thermal equilibrium had been established (10-15 min.), the first ampoule was removed from the bath and placed in an ice-bath (dry-ice ethanol for the solvolysis of (21) in buffered hexafluoropropan-2-ol). The ampoule was brought to room temperature and opened; an aliquot (ca. 5.0ml, withdrawn with a constant volume pipette) of the solution was added to acetic acid (5.0ml) containing 1% acetic anhydride and titrated against standardized perchloric acid (ca. 0.01M) in acetic acid[307] containing 1% acetic anhydride, using crystal

violet as indicator. The remaining ampoules were removed after the appropriate intervals of time and treated in a similar manner. The titres were treated in a manner analogous to that described above for absorbances.

Analysis of the products from the solvolyses

An accurately weighed sample of the *p*-nitrobenzenesulphonate (to give ca. 0.01M solution) was dissolved in a solution of the appropriate buffering agent* in the appropriate solvent. The solution was then sealed under nitrogen in an ampoule and heated at a constant temperature for ca. 10 half lives. After the solution had been cooled, it was added to a separating funnel containing water** and ether***. After the contents of the ampoule had been transferred completely to the separating funnel with the aid of ether***, an accurately weighed sample of the internal standard in ether*** was added to the separating funnel. The layers were separated and the organic layer was washed thoroughly with water****, and dried. The solution was carefully concentrated*** by distilling almost all of the ether through a fractionating column (30cm, Vigreaux) while the temperature of the bath

---

* Sodium ethoxide in ethanol was prepared by adding the appropriate amount of sodium to ethanol. For the solvolysis of (23) 0.025M solutions of ester were used. In this case the solutions were 0.05M in triethylamine.

** In the case of 3-(cyclohex-1'-enyloxy)propyl *p*-nitrobenzenesulphonate, 2% sodium carbonate was used in place of water.

*** For the solvolysis of 4-pentenyl *p*-nitrobenzenesulphonate, purified decalin or *n*-decane were used as the solvent; in this case concentration was not carried out.

**** If the presence of peaks due to trifluoroethanol or hexafluoropropan-2-ol caused difficulties in the g.l.c. analysis, the organic layer was washed thoroughly with 10% aqueous sodium hydroxide; it was shown, in all such cases, that the yields of products obtained was not affected by repeated washing with sodium hydroxide solution.

was maintained at ca. 45°. The final concentrate, after cooling the flask in ice and washing the column with a small quantity of ether, was analysed by g.l.c. as follows:

Quantitative analyses. In order to estimate the absolute yield of products, the responses (to the detector of the g.l.c. apparatus) of the authentic compounds with respect to the internal standard were determined (in duplicate) by running accurately weighed samples of the internal standard (1-20mg) and the authentic compound (1-20mg) in ether under the conditions of the g.l.c. analysis. Where the authentic sample was not available in a pure state, the response ratio was assumed to be the same as that of a similar compound. The areas of the peaks were determined and with the use of the response ratios, the absolute yields and percentage yields of each of the products were determined. Each product analysis was the average of at least 2 g.l.c. determinations and was carried out in duplicate. The experimentally determined yields of products varied between 90 and 110% except where noted in the text; the percentage yields were normalized to 100%. Where low yields were obtained the analysis of products from the solvolyses was carried out at least five times; in all cases the results were consistent.

Qualitative analyses. Qualitative identifications were made initially by comparing the retention times of the components upon g.l.c. analysis with those of authentic samples and then by peak enhancement ("spiking"). In most cases, the "spiking" was carried out on 3 g.l.c. columns with liquid phases of widely differing characteristics.

Sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide

To hexafluoropropan-2-ol (84.0g; 0.50 mole) in a flask, sodium hydroxide (18g; 0.45 mole) was added and the mixture heated under reflux for 1 hr. A further portion of hexafluoropropan-2-ol (20ml) was added and the mixture was heated under reflux for 20 hr. The mixture was cooled and the solid (15.4g, 18% yield) was filtered off* and recrystallized from a large volume of chloroform. The solid was thoroughly dried *in vacuo* and stored in a stoppered bottle inside a dessicator, m.p. 69-69.5° (lit.,[308] 68°; lit.,[309] 68-70°).**

---

* Unchanged hexafluoropropan-2-ol was recovered by distillation from anhydrous calcium sulphate.

** A m.p. of 114-116° has been reported;[310] interestingly, these workers also reported that no reaction occurs when sodium and neat hexafluoroprop-2-ol are mixed. This was confirmed in these laboratories; in the presence of ether, however, a reaction occurs.

Work described in Chapter 1

3-(Cyclohex-1'-enyloxy)propyl *p*-nitrobenzenesulphonate (54)

Treatment of 3-(cyclohex-1'-enyloxy)propanol (61)[192,193] with *p*-nitrobenzenesulphonyl chloride as described[192,193] gave the required sulphonate (54), m.p. 79-80° (lit.,[192] 75-76°).

3-Cyclohexyloxypropyl *p*-nitrobenzenesulphonate (59)

The ester (59), m.p. 50.5-51.5° (lit.,[192] 48.5-49.5°) was prepared from 3-cyclohexyloxypropanol as described.[192]

4-Cyclohexylbutyl *p*-nitrobenzenesulphonate (60)

4-Cyclohexylbutanol*[1] was treated with *p*-nitrobenzenesulphonyl chloride as described by Gream[1] to give the sulphonate (60), m.p. 63.5-64.0° (lit.,[1] 63.5-64.5°).

3-(Cyclohex-1'-enyloxy)propyl ethyl ether (56)

To a stirred mixture of 3-(cyclohex-1'-enyloxy)propanol (61) (1.77g; 0.011 mole) in dimethylformamide under a nitrogen atmosphere, sodium hydride (1.63g; 50% oil dispersion; 0.034 mole) was added. The mixture was warmed to 100-110° and ethanol (3 drops) followed by ethyl iodide (3.43g; 0.022 mole) was added. The mixture was stirred at 90-100° for 3 hr. and then cooled, diluted with water and extracted with ether. The ether extract was dried, concentrated and the residue

---

* A sample of this alcohol was also prepared in 85% yield by catalytic hydrogenation (Adam's catalyst) of 4-phenylbutanol at room temperature and atmospheric pressure.

was distilled, b.p. 74-77°/0.7mm (lit.,[192] 70° (short path)/1mm). The colourless liquid (46% yield) was homogeneous by g.l.c. (column B). ν_{max} 3090w, 2960s, 2890s, 1670s, 1445m, 1375s, 1185s, 1115s, 785m; n.m.r. δ4.55 (1H, unresolved triplet), 3.83-3.20 (6H, 2 overlapping triplets and 1 quartet, J 6Hz), 2.23-0.8 (10H, complex), 1.17 (3H, triplet, J 6Hz).

Cyclohex-1-enyl allyl ether (62)

The elimination of 1 equivalent of allyl alcohol from cyclohexanone diallyl acetal[195,196] as described[197] gave cyclohex-1-enyl allyl ether, b.p. 63.5-64°/8mm (lit.,[197] 75-78°/16mm). Attempted purification by preparative t.l.c. on basic alumina resulted in decomposition. Repeated distillation gave a sample which was homogeneous by g.l.c. (column B).

2-Allylcyclohexanone (63)

Distillation of the residue from the preparation of cyclohex-1-enyl allyl ether (62) afforded 2-allylcyclohexanone (63)[197,198] b.p. 63-64°/0.7mm (lit.,[198] 86-88°/15mm). Preparative t.l.c. on silica gel followed by distillation gave a sample which was homogeneous by g.l.c. (column B).

3,4-Dihydro-2H-1-benzopyran (65)

The Friedel-Crafts cyclization of 1,3-diphenoxypropane[200] as described[200] gave 3,4-dihydro-2H-1-benzopyran (65), b.p. 92-100°/17mm (lit.,[200] 96-100°/16mm). G.l.c. analysis (column B) showed that the purity was 99.5%.

3,4,5,6,7,8-Hexahydro-2H-1-benzopyran (64)

3,4-Dihydro-2H-1-benzopyran (65) was reduced with lithium in dimethylamine/ethylamine as reported[199] to give the required enol ether (64), b.p. 79-83°/17mm (lit.,[199] 68-72°/10mm). G.l.c. analysis (column B) indicated that the purity was 98%.

8aα and β-Ethoxy-3,4,4aα,5,6,7,8,8a-octahydro-2H-1-benzopyran (66a) and (66b)

(i) The enol ether (64) (0.96g; 7.0 mmole), ethanol (2ml) and *p*-toluenesulphonic acid (0.1g) were mixed together and heated under reflux. Samples were withdrawn periodically by syringe and added to 10% sodium carbonate solution and extracted with ether. Each ether layer was dried and analysed by g.l.c. (column B). After the reaction had gone to completion (3 hr.), the mixture was worked up as described above to give a mixture (14:86) of the ethers (66a) and (66b) in 53% yield. ν_{max} 2960s, 2880s, 1465s, 1450s, 1205m, 1115s, 1100s, 1085s, 1055s, 1000s, 965s, 860m, 790s, 770m; n.m.r. δ3.93-3.07 (4H, multiplet), 2.10-0.9 (16H, multiplet, includes a triplet δ1.12, J 7Hz).

The reaction was repeated with heating under reflux continued for 4 days; the same ratio of products was observed.

Attempts to separate the two isomers by preparative g.l.c. (columns K and L) resulted in decomposition. Column chromatography on basic alumina gave a sample of the *trans* isomer (66b),* ν_{max} 2960s, 2880s, 1450s, 1205s, 1115s, 1100s, 1085s, 1055s, 1000s, 965s, 860m, 790w, n.m.r. δ3.52 (2H, unresolved triplet), 3.37 (2H, quartet, J 7.5Hz),

* Tentative assignment of stereochemistry (see p. 37).

2.03-0.83 (16H, complex, includes triplet δ1.17, J 7.5Hz). This sample was homogeneous by g.l.c. (column B); distillation (b.p. 50°(short path)/0.01mm), however, resulted in some decomposition. Samples of (66b) which were stored in ampoules (sealed under nitrogen) at -15° for 1 week were found, when opened, to have decomposed completely to the enol ether (64). For these reasons, a satisfactory elemental analysis could not be obtained.

(ii) The solvomercuration-demercuration[201] of (64) with mercuric acetate in the presence of ethanol gave a mixture (14:86) of (66a) and (66b) in 71% yield. Whenever the reduction of the oganomercurial intermediate was carried out using sodium amalgam,[311] only starting material was obtained.

8aα-(2',2',2'-Trifluoroethoxy)-3,4,4aα,5,6,7,8,8a-octahydro-2H-1-benzopyran (67a)*

(i) The sulphonate (54) (0.84g; 0.0025 mole) was dissolved in trifluoroethanol (25ml) containing triethylamine (1.0g; 0.01 mole); the mixture was heated at 30° for 16 hr. and then added to 2% aqueous sodium carbonate and extracted with low boiling petroleum. The layers were separated and the aqueous phase was extracted with low boiling petroleum (2 × 50ml). The combined organic extracts were washed successively with 2% aqueous sodium carbonate, 10% aqueous sodium dihydrogenphosphate and 2% aqueous sodium carbonate. The solution was dried and concentrated and the residue was chromatographed on basic alumina to give the trifluoroethyl ether (67a). G.l.c. analysis

---

* Tentative assignment of stereochemistry (see p. 38).

(column B) showed that the purity was 98%. ν_{max} 2960s, 2880s, 1280s, 1155s, 1105s, 1025s, 875s, 830s, 670m; n.m.r. δ3.80 (2H, quartet, J 8.5Hz), 3.63 (2H, unresolved triplet), 2.53-0.70 (13H, complex); mass spectrum: m/e 238 (20%), 195 (100). Further chromatography on basic alumina did not increase the purity. Distillation or preparative g.l.c. resulted in decomposition and consequently a satisfactory elemental analysis could not be obtained (Found: C, 57.2; H, 7.6; F, 23.8. $C_{11}H_{17}F_3O_2$ requires: C, 55.5; H, 7.2; F, 23.9%).

(ii) The solvomercuration-demercuration[201] of (64) with mercuric acetate in the presence of trifluoroethanol gave a mixture (16:84) of the ether (67a) and starting material, respectively.

The use of freshly prepared mercuric trifluoroacetate[201] gave the same result.

(iii) A trace of *p*-toluenesulphonic acid was added to a mixture of the enol ether (64) (0.123g) and trifluoroethanol (5ml). The mixture was heated under reflux for 0.5 hr. and an aliquot was withdrawn and added to 10% aqueous sodium carbonate and ether. The ether layer was separated, dried and then analysed by g.l.c. (column B). The remaining reaction mixture was heated under reflux for 8 hr. and treated similarly. Both aliquots contained a mixture of the ether (67a) and starting material (16:84).

Work described in Chapter 2

4-(2'-Oxacyclohex-1'-enyl)but-1-ene (75)

The addition of but-4-enylmagnesium bromide to δ-valerolactone as described[194,225] gave the required olefin (75), b.p. 42-42.5/4mm (lit.,[194] 51-53/3mm). The yield of product (75) was found to be variable; the following percentage yields were obtained (the weight of δ-valerolactone that was used is in brackets): 28% (6.25g), 10 (12.5), 15 (20.4), 24 (27.8), 8 (37.5), 13 (43.5) and 6 (50.0). In all cases freshly redistilled 4-bromobutene and δ-valerolactone were used.

5-(But-3'-enyl)non-8-en-1,5-diol (76)

The residue, b.p. 122-122.5°/0.1mm, from the above reaction was distilled to give the diol (76). ν_{max} 3360s and b, 3095s, 2960s, 2890s, 1645s, 1450s, 1160s, 1000s, 820s; n.m.r. δ6.22-5.45 (2H, multiplet), 5.25-4.72 (4H, multiplet), 4.10 (1H, broad, exchanges with D_2O), 3.55 (2H, triplet, J 6Hz), 2.75 (1H, broad), 2.38-1.17 (14H, complex); mass spectrum: m/e 212 (2%), 79 (100). Redistillation resulted in the loss of one equivalent of water, b.p. 109-110/2mm (Found: C, 80.1; H, 11.6. $C_{13}H_{22}O$ requires: C, 80.4; H, 11.4%).

4-(2'-Oxacyclohex-1'-enyl)butanol (78)

(i) 2-Methylbut-2-ene (2.28g; 0.033 mole; freshly redistilled), diglyme (10ml, freshly redistilled from lithium aluminium hydride) and sodium borohydride (0.62g; 0.016 mole; 33% excess) were placed in a flask under a nitrogen atmosphere. The flask was cooled to 0° and boron trifluoride etherate (2.31g; 0.016 mole; freshly redistilled) was added

dropwise with stirring. After the solution had been stirred for 16 hr. at 0°, the olefin (75) (1.0g; 0.0072 mole) was added all at once. The solution was stirred at room temperature for 8 hr. and water (0.5ml) followed by 3M aqueous sodium hydroxide (5.2ml) were added. Hydrogen peroxide (30%; 5.2ml)* was added dropwise and the mixture was warmed at 45-50° for 1 hr. The mixture was diluted with water and then extracted with ether; the ether extract was washed twice with 2% aqueous sodium hydroxide and then dried and concentrated. The residue was distilled to give the required alcohol, b.p. 80-80.5°/0.4mm (lit.,[194] 79-81°/0.4mm) in 25-58% yield.** (Found: C, 69.4; H, 10.5. $C_9H_{16}O_2$ requires: C, 69.2; H, 10.3%).

(ii) Repetition of this reaction on a larger scale (4.23g of the olefin (75)), gave after distillation, a mixture (ca. 50:50) of the required alcohol (78) and an unidentified product (ν_{max} 1725cm^{-1}). Fractional distillation (b.p. 80-80.5°/0.4mm), did not give any separation; preparative t.l.c. on basic alumina at 4° gave two fractions. The fraction of lowest R_f was a keto-alcohol; the other fraction was identified as 1,7-dioxaspiro[5.5]undecane (79).

(iii) The use of 1 equivalent of bis-(3-methylbut-2-yl)borane (77) gave only starting material.

(iv) The hydroboration was repeated using 4.5 equivalents of borane (77); distillation of the reaction mixture gave 3-methylbutan-2-ol but none of the alcohol (78) was obtained. Both the n.m.r. and

---

* Hydrogen peroxide was titrated against standardized ceric sulphate solution.[312]

** The alcohol was homogeneous by g.l.c. (column C); the retention time, however, was identical to that of 1,7-dioxaspiro[5.5]undecane (79).

infrared spectra of the residue showed the absence of the double bond or enol ether functions.

1,7-Dioxaspiro[5.5]undecane (79)

4-(2'-Oxacyclohex-1'-enyl)butanol (78) (ca. 30mg) was dissolved in carbon tetrachloride.* The n.m.r. spectrum of this sample was identical to that reported for 1,7-dioxaspiro[5.5]undecane (78).[313] Distillation gave a colourless liquid (ca. 30mg), b.p. 80° (block)/22mm, η_D^{20} 1.4638 (lit.,[313] 1.4639); mass spectrum: m/e 156 (15%), 98 (100). The i.r. spectrum was identical to that reported;[313] the sample was homogeneous by g.l.c. (column C).

A further sample of the alcohol (78) was dissolved in carbon tetrachloride which had been passed through a column of sodium hydroxide pellets and the n.m.r. spectrum was recorded immediately; the spectrum was that expected for the alcohol (78). After 10 min., however, the spectrum had changed to that of 1,7-dioxaspiro[5.5]undecane (79). When carbon tetrachloride which had been passed through a column of alumina was used, the n.m.r. spectrum of the alcohol (78) was unchanged after standing at 35° for 1 hr.

Attempted preparation of 4-(2'-oxacyclohex-1'-enyl)butyl *p*-nitrobenzenesulphonate (55)

The alcohol (78) was treated with *p*-nitrobenzenesulphonyl chloride as described.[194] On one occasion, a pale yellow solid was obtained. The solid was added to sodium dried ether; after about half

---

* Spectroscopic grade containing 1% tetramethylsilane.

of the solid had dissolved, the colour of the solid changed from pale yellow to white. At the same time a white solid precipitated from solution; the solid was filtered. The infrared spectrum of the solid indicated the absence of an enol ether. No material was obtained upon concentrating the filtrate.

All other attempts at preparing (55) gave oils; the infrared spectra of these oils indicated the absence of an enol ether.

Attempted preparation of 4-(2'-oxacyclohex-1'-enyl)butyl napthalene-2-sulphonate

Napthalene-2-sulphonyl chloride (0.88g; 3.9 mmole; freshly recrystallized) was added with stirring to a mixture of the alcohol (78) (0.41g; 2.6 mmole) and pyridine (10ml) at 0°. The mixture was stirred at 0° for 40 min. and then pyridine (0.5ml) containing 3 drops of water was added and the mixture was stirred at 0° for a further 10 min. The mixture was poured onto ice with rapid stirring; the ice-water was extracted with ether and the ether layer was dried and concentrated to give an oil. The oil was dried at 0°/0.1mm for 20 min. The oil did not crystallize from ether/light petroleum or carbon tetrachloride/light petroleum. All absorptions in the infrared spectrum of the oil could be attributed to either the alcohol (78) or the sulphonyl chloride. Continuing the reaction for 3 days gave an oil whose infrared spectrum was identical, except that the bands ascribed to the alcohol (78) were much weaker.

6-Methylnapthalene-1-sulphonyl chloride (82)

Treatment of sodium 6-methylnapthalene-1-sulphonate[228] with

thionyl chloride as described[228] gave the required sulphonyl chloride (82), m.p. 98-98.5° (lit.,[228] 98-99°; lit.,[314] 97-98°).

2-Phenylethyl 6-methylnapthalene-1-sulphonate (83)

(i) A mixture of 2-phenylethanol (0.10g), pyridine (2ml) and the sulphonyl chloride (82) (0.20g) was stirred at 0° for 5 days. The mixture was poured onto ice with rapid stirring. The solid (100% yield) was collected, dried *in vacuo* and recrystallized from carbon tetrachloride/light petroleum, m.p. 95-95.5° (lit.,[228] 101.9-102.5°).

(ii) A mixture of 2-phenylethanol (0.10g), pyridine (0.10g), ether (2ml) and the chloride (82) (0.20g) was stirred at 0° for 5 days. Work-up as above gave the sulphonate in 70% yield.

(iii) A mixture of 2-phenylethanol (0.10g), potassium hydride (0.20g; 50% oil dispersion) and dimethylformamide (5ml) was stirred at -15° for 1 hr. The sulphonyl chloride (0.20g) was added and the mixture was stirred at -15° for 30 min. and then poured onto ice-water with rapid stirring. The crystals were collected and shown to be 6-methylnapthalene-1-(N,N-dimethylsulphonamide) (84) by comparison to an authentic sample (see below); the yield was ca. 50mg.

(iv) 2-Phenylethanol (0.10g), dimethylformamide (10ml) and the chloride (82) (0.20g) were stirred together and cooled to 0°. Potassium hydride (0.70g; 50% dispersion) was added and the mixture was stirred at 0° for 4 hr. and then poured onto ice to give the sulphonate (83) in 70% yield.

6-Methylnapthalene-1-(N,N-dimethylsulphonamide) (84)

6-Methylnapthalene-1-sulphonyl chloride (82) (2.40g) and dimethylamine (15ml) were stirred together in a flask fitted with an acetone-dry ice condenser for 5 hr. The dimethylamine was allowed to evaporate overnight; the last traces were removed *in vacuo*. The white crystalline solid (100% yield) was recrystallized twice from carbon tetrachloride, m.p. 116-116.5° (Found: C, 62.6; H, 6.0. $C_{13}H_{15}NO_2S$ requires: C, 62.6; H, 6.1%). ν_{max} 1625w, 1590w, 1330s, 1150s, 950m, 895m, 825m, 805m, 745m, 705s; n.m.r. δ8.38-7.33 (6H, multiplet), 2.78 (6H, singlet), 2.60 (3H, singlet); mass spectrum: m/e 249 (5%), 42 (100).

Attempted preparation of 4-(2'-oxacyclohex-2'-enyl)butyl 6-methylnapthalene-1-sulphonate (80)

(i) 4-(2'-Oxacyclohex-2'-enyl)butanol (78) (0.10g), pyridine (2ml), and the sulphonyl chloride (82) (0.15g) were stirred together at 0° for 16 hr. The mixture was poured onto ice-water and extracted with ether (3 × 20ml). The ether layer was separated, dried and concentrated to give an oil. The infrared spectrum showed the absence of an enol ether function.

(ii) The alcohol (78) (0.10g), pyridine (0.10g), the sulphonyl chloride (82) (0.23g) and ether (4ml) were stirred together at 0° for 3 days. Pyridine (0.1ml) and water (0.1ml) were mixed together and added to the above mixture; the solution was stirred at 0° for 8 hr. and then poured onto ice and extracted with ether. The ether layer was separated, dried and concentrated to give an oil. The addition of ether and light petroleum to this oil gave a gum; the infrared spectrum

of the gum showed the absence of any enol ether.

(iii) The alcohol (78) (0.10g), the sulphonyl chloride (82) (0.23g) and dimethylformamide (10ml) were stirred together at -15°. Potassium hydride (0.08g; 50% oil dispersion) was added and the mixture was stirred at -15° for 30 min. Water (2 drops) was added and the mixture was stirred at 0° for 10 min. and then poured onto ice-water and extracted with ether. The ether layer was separated and washed with 2% aqueous sodium carbonate, dried and concentrated. Upon adding ether-light petroleum an unidentified crystalline solid was obtained. The infrared spectrum of the solid indicated the absence of an enol ether function.

1-Chloro-4-iodobutane (89)

1-Chloro-4-iodobutane (89) was prepared from 1,4-dichlorobutane[315] in 70% yield as described,[316] b.p. 95-98°/23mm (lit.,[316] 93-94.5°/17mm; lit.,[317] 82°/10mm).

1-Bromo-4-iodobutane (90)

To a stirred solution of 1,4-dibromobutane (200g; 0.93 mole) in acetone,* anhydrous sodium iodide** (46.3g; 0.31 mole) was added. The mixture was heated under reflux for 2 hr. and then cooled and filtered. Fractional distillation gave recovered 1,4-dibromobutane and 1-bromo-4-iodobutane (23.7g; 29% yield) b.p. 60-64°/1mm. The sample, b.p. 52-53°/1mm was redistilled (Found: C, 18.6; H, 3.2. C_4H_8BrI requires:

---

* Acetone was dried over anhydrous calcium sulphate for 2 hr. and then filtered and distilled; it was stored over 4A molecular sieves.

** Sodium iodide was dried at 115°/0.2mm for 24 hr.

C, 18.3; H, 3.1%). ν_{max} 3020w, 2972s, 2947s, 2920m, 2880w, 2855m, 1465m, 1455s, 1440s, 1250s; n.m.r. δ3.37 (2H, triplet, J 6Hz), 3.18 (2H, triplet, J 6Hz), 2.23-1.67 (4H, multiplet); mass spectrum: m/e 264/262 (0.1%), 183 (22), 137/135 (33), 55 (100).

Attempted preparation of 4-(2'-oxacyclohex-1'-enyl)butyl chloride (87)

(i) To a stirred mixture of redistilled 3,4-dihydro-2H-pyran (10.0g; 0.12 mole) and anhydrous tetrahydrofuran (4.30g; 0.060 mole) at 0°, t-butyllithium (150ml of a 1.2M pentane solution)* was added under a nitrogen atmosphere. The mixture was stirred at 0° for 1 hr. and then tetrahydrofuran (10ml) was added. 1-Chloro-4-iodobutane (26.2g; 0.12 mole) was added dropwise with stirring at 0°; the mixture was stirred at 0° for 2 hr. and then at room temperature for 1 hr. Hexamethylphosphoric triamide (50ml)** and ether (100ml) were added and the mixture was stirred at room temperature for 16 hr. Water was added and the layers were separated; the aqueous phase was extracted with ether and the combined ether extracts were washed successively with 5% aqueous sodium metabisulphite and 2% aqueous sodium carbonate and then dried and concentrated. The residue was distilled through a micro spinning band column*** to give a colourless liquid (2.7g), b.p. 78-79°/0.5mm. The n.m.r. spectrum was consistent with an impure sample of the chloride (87). Column chromatography on basic alumina resulted in decomposition.

---

* Titrated with diphenylacetic acid as described.[318]

** When hexamethyphosphoric triamide (1 equivalent) was added before 1-chloro-4-iodobutane, none of the required product was detected after work-up.

*** Perkin Elmer model 131 Microstill, column size 6mm × 20cm.

(ii) Dihydropyran (2.0g; 0.024 mole) and tetrahydrofuran (1.03g; 0.014 mole) were stirred together and cooled to -78°. t-Butyllithium (26ml of a 1.1M pentane solution) was added to the stirred solution under nitrogen and the solution was allowed to warm to 0°. 1-Chloro-4-iodobutane (6.29g; 0.029 mole) was placed in a dropping funnel and about half of it was added dropwise to the above solution at 0°; hexamethylphosphoric triamide (4.30g; 0.024 mole) was added at 0° followed by the remaining iodochlorobutane. The mixture was allowed to warm to room temperature and then stirred for 30 min. Water was added to the mixture followed by ether. The layers were separated and the ether layer was washed with 2% aqueous sodium carbonate and then dried and concentrated. The residue was distilled to give the following two fractions: (i) 0.17g, b.p. 48-56°/0.2mm; n.m.r. ($CDCl_3/CCl_4$ ca. 1:1) δ4.42 (1H, triplet, J 3Hz), 3.92 (2H, triplet, J 5Hz), 3.50 (3H, two overlapping triplets, J 6Hz), 3.20 (1H, triplet, J 6Hz), 2.45-0.80 (17H, complex, includes singlets at 0.98, 0.92 and 0.85); (ii) 0.36g, b.p. 56-58°/0.2mm, n.m.r. δ4.35 (1H, triplet, J 3Hz), 3.87 (2H, triplet, J 5Hz), 3.43 (2H, triplet, J 6Hz), 2.6 (0.5H, doublet or two singlets, J 9Hz), 2.42-0.80 (15H, complex, includes singlets at 1.00, 0.92 and 0.87). Preparative g.l.c. (column H) resulted in decomposition.

(iii) The alcohol (78) (140mg; 0.90 mmole) was dissolved in carbon tetrachloride (0.5ml) containing 1% 2,6-lutidine in an n.m.r. tube. Triphenylphosphine (260mg; 1.0 mmole) was added and the n.m.r. spectrum was recorded at regular intervals. The spectra showed that the alcohol was isomerizing to 1,7-dioxaspiro[5.5]undecane (79); the conversion was complete after 1 hr.

(iv) The above reaction was repeated with carbon tetrachloride containing 5% 2,6-lutidine; after 4.5 hr. at room temperature the alcohol (78) was unchanged. The mixture was heated at 60° for 10 hr. and the n.m.r. spectrum was recorded; the spiro compound (79) again had been formed.

(v) The alcohol (78) (33mg; 0.21 mmole) was dissolved in carbon tetrachloride containing 1% 1,6-lutidine. Tri-n-butylphosphine (47mg; 0.23 mmole) was added and an exothermic reaction took place. Once again the alcohol was converted to the spiro compound (79).

(vi) Tri-n-butylphosphine (47mg; 0.23 mmole) was added to carbon tetrachloride; an exothermic reaction took place. After the solution had cooled to room temperature, the alcohol (78) (33mg; 0.21 mmole) was added and the n.m.r. spectrum was recorded. The spectrum indicated the absence of alcohol (78) and the presence of (79).

Attempted preparation of 4-(2'-oxacyclohex-1'-enyl)butyl bromide (88)

To a stirred mixture of redistilled 3,4-dihydro-2H-pyran (2.0g; 0.024 mole) and tetrahydrofuran (1.03g; 0.014 mole), t-butyllithium (14ml of a 2M solution in pentane) was added at -10° under an atmosphere of nitrogen. After stirring at 0° for 1 hr. the mixture was diluted with tetrahydrofuran and added dropwise to a stirred mixture of 1-bromo-4-iodobutane (6.3g; 0.024 mole), hexamethylphosphoric triamide (4ml) and tetrahydrofuran (20ml) at 0° under a nitrogen atmosphere. The mixture was stirred at room temperature for 1 hr. and then diluted with ether. Water was added and the layers were separated; the ether layer was washed with 2% aqueous sodium carbonate (3 × 200ml), dried and concentrated. The residue was distilled to give two fractions,

b.p. 68-75°/0.6mm (0.74g) and b.p. 75-77°/0.6mm (1.30g); the n.m.r. spectrum of both of these fractions was consistent with a mixture of the required bromide (88) and at least one impurity. G.l.c. analysis (column B) suggested that decomposition on the column was occurring. Dry column chromatography on alumina at room temperature using carbon tetrachloride as solvent gave a low yield of a mixture of the bromide (88) and at least three other impurities. Chromatography on alumina at 3° using 30-40 petrol as solvent gave a good recovery of a colourless oil whose n.m.r. spectrum was consistent with a mixture of the required bromide (88) and at least one other component; fractional distillation gave a partial separation. The purest fraction that was obtained exhibited the following n.m.r. spectrum: δ4.32 (1H, triplet, J 3Hz), 3.85 (2H, triplet, J 5Hz), 3.28 (2H, triplet, J 6Hz), 3.20 (0.5H, triplet, J 6Hz), 2.50-1.22 (12H, multiplet).

4-(2'-Oxacyclohex-1'-enyl)butyl *p*-nitrobenzoate (92)

4-(2'-Oxacyclohex-1'-enyl)butanol (78) (100mg; 0.64 mmole) was added under a nitrogen atmosphere to a mixture of potassium hydride (60mg; 0.77 mmole; 50% oil dispersion) and hexamethylphosphoric triamide (5ml). After the mixture had been stirred at room temperature for 10 min., it was cooled to 0° and freshly recrystallized *p*-nitrobenzoyl chloride (107mg; 0.58 mmole) was added. The mixture was stirred at 0° for 30 min. and then poured onto ice and extracted with ether. The ether layer was washed with 2% aqueous sodium hydroxide (3 × 300ml) and then dried and concentrated to give a yellow oil. The infrared spectrum was consistent with the ester (92); the n.m.r. spectrum, however, indicated that the purity was less than 25%. Repeated attempts at obtaining a crystalline sample from ether, light

petroleum, toluene or carbon tetrachloride were unsuccessful.

The reaction was repeated twice so that a total of 300mg of alcohol (78) was used; in all cases the n.m.r. spectrum of the oils obtained showed that the yield of ester was less than 40%. The three reaction mixtures were combined and a small amount of crystalline material (20mg) was obtained by crystallization from light petroleum at -15°, n.m.r. δ8.13 (4H, singlet), 4.28 (3H, triplet overlapping a poorly resolved triplet), 3.50 (2H, triplet, J 6Hz), 2.57-2.23 (4H, complex), 1.90-1.27 (6H, complex); ν_{max} 2980s, 2900s, 1735s, 1693s, 1612s, 1535s, 1275s, 1065s, 995s, 880m, 720s.

The solution which was decanted from the solid was chromatographed on alumina (dry column); 1,7-dioxaspiro[5.5]undecane (79) (ca. 90mg) was the only product detected.

4-(2'-Oxacyclohex-1'-enyl)butyl 3,5-dinitrobenzoate (93)

(i) To n-butyllithium (0.64 mmole) in hexane, the alcohol (78) (100mg; 0.64 mmole) in tetrahydrofuran was added; the mixture was stirred at room temperature under a nitrogen atmosphere for 30 min. A solution of freshly recrystallized 3,5-dinitrobenzoyl chloride[319] (148mg; 0.64 mmole) in tetrahydrofuran was added dropwise to the above solution. The mixture was stirred at room temperature for 1 hr. and then poured onto ice and extracted with ether. The ether extract was washed with 2% aqueous sodium hydroxide, dried and concentrated to give a brown oil. Chromatography on analytical alumina t.l.c. plates (MERCK) gave the required ester, m.p. 42-45° in 18% yield after one recrystallization from light petroleum.

(ii) A mixture of alcohol (78) (110mg; 0.71 mmole) and pyridine (5ml) were cooled to 0° and freshly recrystallized 3,5-dinitrobenzoyl chloride[319] (244mg; 1.06 mmole) was added. The mixture was stirred at 0° for 30 min. and then at room temperature for 30 min. Water (2 drops) was added and the mixture was stirred for a further 10 min. and then poured onto ice and extracted with ether. The ether extract was washed with 2% aqueous sodium hydroxide, dried and concentrated. The yellow oil was chromatographed on analytical alumina t.l.c. plates (MERCK) to give 131mg (53% yield) of a pale yellow oil. The required ester (93) was crystallized from ether-light petroleum, m.p. 43-45°. A further recrystallization from light petroleum gave m.p. 46.5-47.5° (Found: C, 54.9; H, 5.1. $C_{16}H_{18}N_2O_7$ requires: C, 54.9; H, 5.2%). ν_{max} 3100m, 1730s, 1680s, 1650s, 1600m, 1550s, 1270s, 1160s, 1060s, 915s, 725s; n.m.r. δ9.08-8.88 (3H, complex), 4.37 (3H, triplet, J 6Hz overlapping an unresolved triplet), 4.03 (2H, triplet, J 6Hz), 2.22-1.22 (10H, complex); mass spectrum: m/e 350 (8%), 98 (100).

Work described in Chapter 3

3-(Cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate (27)

Treatment of 3-(cyclohex-1'-enyl)propanol[2] with *p*-nitrobenzenesulphonyl chloride and pyridine as described[2] gave the required ester (45% yield), m.p. 71.5-72.5° (lit.,[2] 71.5-72.5°) after recrystallization from ether/light petroleum.

3-Cyclohexylpropyl *p*-nitrobenzenesulphonate (95)

The ester (95) (24% yield), m.p. 80.5-81.5° (lit.,[2] 80.5-81.0°; lit.,[81] 80-81°) was obtained from 3-cyclohexylpropanol[2] as described.[2]

N-(3-cyclohexylpropyl)pyridinium *p*-nitrobenzenesulphonate, m.p. 124-125°, was obtained as a by-product in 28% yield.* ν_{max} 3080w, 3050w, 1640m, 1600m, 1520s, 1490m, 1225s, 1205s, 1120s, 1030s, 1010s, 873m, 855m, 735s, 685s; n.m.r. ($CDCl_3$) δ9.33 (2H, doublet of doublets, J 2 and 6Hz), 8.95-7.80 (7H, multiplet), 4.78(2H, triplet, J 7Hz), 2.30-0.50 (15H, complex). On one occasion this product was the only product obtained.

4-Pentenyl *p*-nitrobenzenesulphonate (26)

The general procedure of Tipson[232] gave the required ester m.p. 45-46° (lit.,[60] 45-46°) in 64% yield after recrystallization from light petroleum.

---

* It was found that the formation of this product could be avoided by removing all traces of pyridine from the crude solid before recrystallization; the pyridine was removed at 0°/0.1mm.

n-Pentyl *p*-nitrobenzenesulphonate (96)

The Tipson procedure[232] gave the required ester, m.p. 57-57.5° (lit.,[320] 56°) in 32% yield after recrystallization from light petroleum.

1-Allylcyclohex-1-ene (94)

The diene (94), b.p. 154-155° (lit.,[321] 154-155°; lit.,[2] 155-156°) was prepared in 65% yield by the dehydration of 1-allylcyclohexanol[2] as described.[2]

3-Cyclohexylpropyl 2,2,2-trifluoroethyl ether (98)

To a flask equipped with a wide leak tube and connected to two traps (connected in series) cooled to -78° was added trifluoroethanol (5ml). The mixture was cooled in ice and sodium hydride (0.59g; 0.012 mole; 50% oil dispersion) was added and the mixture was stirred at room temperature for 5 min.; hexamethylphosphoric triamide (10ml) was added followed by 3-cyclohexylpropyl *p*-nitrobenzenesulphonate (95) (2.0g; 6.1 mmole). A stream of nitrogen was bubbled through the solution in the distillation flask and the solution was heated at 130° for 4 hr.; the nitrogen flow was continued throughout. The volatile products which had collected in the cold traps were diluted with low boiling petroleum and water. The layers were separated and the organic phase was washed successively with water, 5% aqueous sodium hydroxide and water and then dried. The solution was carefully concentrated by fractional distillation and the concentrate was purified by preparative g.l.c. (column L). Distillation gave the required ether, b.p. 180° (block) in 34% yield. G.l.c. analysis (column C) showed that the ether

was homogeneous (Found: C, 58.5; H, 8.4. $C_{11}H_{19}F_3O$ requires: C, 58.9; H, 8.5%). ν_{max} 2910s, 2835s, 1430m, 1250s, 1130s, 845m; n.m.r. δ3.76 (2H, quartet, J 8.5Hz), 3.57 (2H, triplet, J 6Hz), 2.10-0.60 (15H, complex); mass spectrum: m/e 224 (0.1%) and 55 (100).

3-(Cyclohex-1'-enyl)propyl 2,2,2-trifluoroethyl ether (97)

A similar procedure to that described above gave the ether (97), b.p. 140° (block)/110mm in 64% yield after distillation. The ether (97) was homogeneous by g.l.c. (column C), (Found: C, 59.1; H, 7.5. $C_{11}H_{17}F_3O$ requires: C, 59.5; H, 7.7%). ν_{max} (CCl_4 soln.) 2920s, 2840s, 1660w, 1430s, 1265s, 1140s, 960s; n.m.r. δ5.43 (1H, broad singlet), 3.77 (2H, quartet, J 8.5Hz), 3.57 (2H, triplet, J 6Hz), 2.30-1.40 (12H, complex); mass spectrum: m/e 222 (15%) and 81 (100).

3-(Cyclohex-1'-enyl)propyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (99)

3-(Cyclohex-1'-enyl)propyl *p*-nitrobenzenesulphonate (27) (1.7g; 5.19 mmole) and hexafluoropropan-2-ol (10ml) containing triethylamine (2.10g; 0.021 mole) were heated together in an ampoule sealed under nitrogen at 98° for 15 hr. After it had been cooled, the ampoule was opened and the contents were diluted with water and extracted with low boiling petroleum. The organic extract was washed successively with water, 5% aqueous sodium hydroxide and water and then dried and carefully concentrated by fractional distillation. The concentrate was purified by preparative g.l.c. (column L); distillation gave the required ether (99), b.p. 120-130° (block)/100mm in 41% yield. The ether was homogeneous by g.l.c. (column C), (Found: C, 50.1; H, 5.7. $C_{12}H_{16}F_6O$ requires: C, 49.7; H, 5.6%). ν_{max} 2960s, 1660w, 1365m,

1280s, 1210s, 1180s, 1095s; n.m.r. δ5.45 (1H, broad singlet), 3.93 (1H, septet, J 6Hz), 3.83 (2H, triplet, J 6Hz), 2.10-1.30 (12H, complex); mass spectrum: m/e 290 (1%), 81 (100).

3-Cyclohexylpropyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (100)

A similar procedure to that described above gave the ether (100), b.p. 120-125° (block)/100mm in 30% yield after one distillation. G.l.c. analysis (column C) showed that the ether was homogeneous, (Found: C, 49.3; H, 6.1. $C_{12}H_{18}F_6O$ requires: C, 49.3; H, 6.2%). ν_{max} 2950s, 2880m, 1370m, 1280s, 1210s, 1185s, 1100s; n.m.r. δ3.95 (1H, septet, J 6Hz), 3.83 (2H, triplet, J 6Hz), 2.00-0.80 (15H, complex); mass spectrum: m/e 292 (1%), 83 (100).

2-Carbethoxy-2-(3'-bromopropyl)cyclohexanone (193)

Alkylation of 2-carbethoxycyclohexanone[193] with 1,3-dibromopropane as described[322] gave the required compound, b.p. 124-130°/0.5mm (lit.,[322] 157/1mm) in 35% yield.

2-(3'-Bromopropyl)cyclohexanone (194)

Hydrolysis and decarboxylation of (193) with a mixture of 48% hydrobromic acid and acetic acid saturated with hydrogen bromide as described[322] gave the keto-bromide (194), b.p. 92-94°/0.4mm (lit.,[322] 123°/1mm) in 41% yield.

3-(2'-Oxocyclohexyl)propyltriphenylphosphonium bromide (195)

The keto-bromide (194) (2.0g; 9.13 mmole) and triphenylphosphine

(2.39g; 9.13 mmole) were dissolved in dry acetonitrile (10ml) and the solution was heated under reflux for 32 hr. The solution was cooled and the solvent was removed under reduced pressure. The glass-like phosphonium salt (195) was repeatedly washed with ether; the last traces of ether were removed under reduced pressure and the phosphonium salt (195) (100% yield) was used without further purification.

Bicyclo[4.3.0]non-1(9)-ene (105)

The phosphonium salt (195) was treated with potassium methylsulphinylmethide* in dimethylsulphoxide in a manner analogous to that described.[59] Preparative g.l.c. followed by distillation gave the olefin (105), b.p. 140-150° (block), (lit.,[59] 137-138°) in 16% yield.

4-Pentenyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (101)

In a flask equipped with an outlet to a cold trap (cooled to -78°) was placed sodium hydride (1.0g; 0.021 mole; 50% oil dispersion) and hexamethylphosphoric triamide (10ml). Hexafluoropropan-2-ol (5ml) was added dropwise with stirring and the mixture was stirred at room temperature for 1 hr. 4-Pentenyl *p*-nitrobenzenesulphonate (26) (2.0g; 7.4 mmole) was added and a stream of nitrogen was bubbled through the solution so that the volatile vapours were collected in the cold trap. The solution was heated at 140° for 4 hr. and then allowed to cool. Hexafluoropropan-2-ol (5ml) was added and the mixture was heated at 140° for a further hour. After the mixture had been cooled, the

---

* The solution of potassium methylsulphinylmethide in dimethylsulphoxide was prepared by adding the appropriate amount of potassium hydride to dimethylsulphoxide and allowing the mixture to stir at room temperature for 30 min.

nitrogen flow was stopped and the contents of the cold trap were diluted with water and extracted with redistilled di-n-butyl phthalate.* The organic extract was washed successively with water, 10% aqueous sodium hydroxide and water and then dried. The hexafluoroprop-2-yl ether, b.p. 28-30°/30mm was distilled from the solvent into a cooled (-78°) receiving flask. Redistillation, b.p. 90° (block) gave a sample of the ether that was homogeneous by g.l.c. (column C); the yield was 46% (Found: C, 40.8; H, 4.4. $C_8H_{10}F_6O$ requires: C, 40.7; H, 4.3%). ν_{max} 3090m, 2830s, 1645s, 1375s, 1285s, 1220s, 1190s, 1140s, 1095s, 920s, 890s, 730s, 680s; n.m.r. δ6.07-5.37 (1H, complex), 4.98 (1H, broad singlet), 4.92 (1H, doublet with fine splitting, J 17Hz), 3.92 (1H, septet, J 6Hz), 3.77 (2H, triplet, J 6Hz), 2.37-1.45 (4H, complex); mass spectrum: m/e 236 (5%), 68 (100).

Cyclopentyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (102)

To a solution of sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide** (3.6g; 0.040 mole) in hexafluoropropan-2-ol (8ml) was added freshly prepared mercuric trifluoroacetate[201] (8.53g; 0.020 mole) and cyclopentene (1.36g; 0.020 mole). After the solution had been stirred at room temperature for 10 min.*** 3M aqueous sodium hydroxide (20ml) was added followed by 0.5M sodium borohydride in 3M aqueous sodium hydroxide

---

* On two occasions, purified decalin was used as the extraction solvent. The required ether, however, could not be cleanly separated from decalin by distillation. Preparative g.l.c. (column L) gave a clean separation, but collection of the volatile ether proved to be difficult.

** No reaction occurred in the absence of sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide.

*** The reaction was followed by removing aliquots at regular intervals of time. Each aliquot was worked-up as described above and analysed by g.l.c. (columns C, F); it was found that longer reaction times gave lower yields of the required ether.

(20ml). The mixture was stirred at room temperature for 2 hr. and then diluted with water and extracted with di-n-butyl phthalate. The layers were separated and the organic layer was washed successively with water, 10% aqueous sodium hydroxide (twice) and water and then dried. The volatile products were distilled from the solution at 25mm pressure; the bath temperature was 140° and the collection flask was cooled in liquid nitrogen. G.l.c. analysis (columns C, F) showed the presence of cyclopentene and two other products. The mixture was distilled and the higher boiling fraction (b.p. 95-100° (block)) was purified by preparative g.l.c. (column L) to give the required ether (102) in 5% yield. A 31% yield of cyclopentanol was also obtained. The ether (102) was dissolved in di-n-butyl phthalate and distilled from it (bath temperature 140°, receiving flask cooled to -78°). Distillation gave a sample of the required ether (102) b.p. 100° (block) which was homogeneous by g.l.c. (column C), (Found: C, 41.0; H, 4.5. $C_8H_{10}F_6O$ requires: C, 40.7; H, 4.3%). ν_{max} 2990s, 2910m, 1435m, 1385s, 1365s, 1280s, 1220s, 1185s, 1125s, 1095s, 970s, 897s, 877s, 725m, 670s; n.m.r. δ4.27 (1H, broad singlet), 3.97 (1H, septet, J 6Hz), 2.00-1.50 (8H, complex); mass spectrum: m/e 236 (9%), 69 (100).

1,5-Pentanediol diacetate

A mixture of 1,5-pentanediol (10.0g; 0.096 mole) and acetic anhydride (19.6g; 0.192 mole) were heated under reflux for 2 hr. The mixture was allowed to cool slightly and water (5ml) was added carefully. The mixture was stirred for 10 min. and then diluted with water and extracted with ether. The ether layer was washed successively with 10% aqueous sodium hydroxide and water and then dried and concentrated.

The residue was distilled to give the required acetate, b.p. 132-134°/ 25mm (lit.,[233] 244°) in 83% yield.

1,4-Pentadiene (106)

1,5-Pentandiol diacetate was pyrolysed at 575°[233] under reduced pressure (25mm). Distillation gave 1,4-pentadiene (106) contaminated with a small amount of acetic acid. Taking into account the acetic acid impurity the yield was 88%. N.m.r. δ6.05-5.23 (2H, complex), 5.12-4.67 (4H, complex), 2.72 (2H, triplet of triplets, J 6 and 2Hz), [lit.,[323] δ_1 4.92, δ_2 4.95, δ_3 5.71, δ_4 2.72, J_{12} 2.2Hz, J_{13} 10.3Hz, J_{14} -1.5Hz, J_{23} 16.9Hz, J_{24} -1.3Hz, J_{34} 6.3Hz].

Work described in Chapter 4

4-Phenylbutyl *p*-nitrobenzenesulphonate (23)

The treatment of 4-phenylbutanol with *p*-nitrobenzenesulphonyl chloride as described[53] gave the required ester, m.p. 66-66.5° (lit.,[53] 63-65°) in 63% yield after two recrystallizations from ether/light petroleum.

4-Cyclohexylbutyl *p*-nitrobenzenesulphonate (60)

See p. 154.

4-Phenylbut-1-ene (112)

Magnesium (1.90g; 0.078 g-atom) and dry ether (100ml) were placed in a flask fitted with a condenser, dropping funnel and nitrogen atmosphere. A solution of benzyl chloride (11.0g; 0.087 mole) in ether (100ml) was added over 1.5 hr. and the mixture was heated under reflux for a further 15 min. After the mixture had been cooled, allyl bromide (10.29g; 0.085 mole) was added over 30 min. and the mixture was stirred at room temperature for 1.5 hr. The mixture was heated under reflux for 30 min. and then allowed to cool. Saturated aqueous ammonium chloride was added and the layers were separated. The organic layer was washed with water and then dried and concentrated by fractional distillation. The residue was distilled to give 4-phenylbut-1-ene, b.p. 116-118°/105mm (lit.,[237] 175-178°/760mm; lit.,[324] 107°/78mm).

4-Phenylbutyl 2,2,2-trifluoroethyl ether (113)

A similar procedure to that described for the ether (98) (p.173)

gave 4-phenylbutyl 2,2,2-trifluoroethyl ether (113), b.p. 150° (block)/ 90mm in 15% yield after one distillation, (Found: C, 62.1; H, 6.4. $C_{12}H_{15}F_3O$ requires: C, 62.1; H, 6.5%). ν_{max} 3080w, 3050m, 2970m, 2900m, 1600m, 1580w, 1275s, 1150s; n.m.r. δ7.21 (5H, singlet), 3.77 (2H, quartet, J 8Hz), 3.62 (2H, triplet, J 6Hz), 2.67 (2H, triplet, J 7Hz), 1.80-1.50 (4H, multiplet); mass spectrum: m/e 232 (5%), 41 (100).

4-Phenylbutyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (114)

A similar procedure to that described for the ether (98) (p.173)* gave 4-phenylbutyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (114), b.p. 110-120° (block)/20mm in 63% yield after two distillations, (Found: C, 52.4; H, 4.8. $C_{13}H_{14}F_6O$ requires: C, 52.0; H, 4.7%). G.l.c. analysis (column C) indicated that the ether was homogeneous. ν_{max} 3100w, 3070w, 3040m, 2960m, 2880m, 1600m, 1580w, 1370s, 1280s, 1220s, 1190s, 1095s, 685s, 670s; n.m.r. δ7.18 (5H, singlet), 3.88 (1H, septet, J 6Hz), 3.78 (2H, triplet, J 6Hz), 2.62 (2H, triplet, J 7Hz), 1.90-1.50 (4H, multiplet); mass spectrum: m/e 300 (15%), 91 (100).

---

* Hexafluoropropan-2-ol and sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide were used instead of trifluoroethanol and its sodium salt (generated *in situ*).

Work described in Chapter 5

3-Cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29)

Treatment of 3-cyclooctatetraenylpropanol[53] with *p*-nitrobenzenesulphonyl chloride and pyridine as described[53] gave the required sulphonate in 94% yield, m.p. 68-69° after one recrystallization from ether/light petroleum. Purification by dry column chromatography on silica gel using toluene as the developing solvent followed by one recrystallization from light petroleum gave yellow needles, m.p. 69.5-70.5° (lit.,[53] 69-70°).*

3-Cyclooctylpropyl *p*-nitrobenzenesulphonate (118)

The procedure described[53] gave the required sulphonate in 85% yield, m.p. 69-70° (lit.,[53] 68-70°) after one recrystallization from light petroleum.

3-Cyclooctatetraenylpropyl 2,2,2-trifluoroethyl ether (120)

Sodium hydride (0.75g; 16 mmole; 50% oil dispersion) and dry hexamethylphosphoric triamide (20ml) were placed in a flask under a nitrogen atmosphere. Dry trifluoroethanol (5ml) was added dropwise and the mixture was stirred at room temperature for 1 hr. Nitrogen was bubbled through the solution and allowed to escape to the atmosphere *via* two traps (cooled with dry-ice) and a drying tube; this stream of nitrogen was continued until the reaction was worked up. 3-Cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) (2.7g; 7.77 mmole)

---

* Poor yields were obtained when this reaction was attempted on greater than ca. 0.5 g of alcohol.

was added and the temperature was raised to 140° and maintained at 140° for 3 hr. The mixture was cooled slightly and trifluoroethanol (5ml) was added and the mixture heated at 140° for a further hour. The contents of the traps were combined and diluted with 10% aqueous sodium hydroxide and low boiling petroleum. The layers were separated and the organic extract was washed successively with 10% aqueous sodium hydroxide, water and then dried. The contents of the reaction flask were treated similarly. The combined product mixtures were chromatographed on silica gel (dry column) using low boiling petroleum as the developing solvent; two fractions were obtained. The fraction of lower R_f gave a sample of the required ether* in 12% yield, b.p. 110° (block)/15mm after one distillation. G.l.c. (column C) analysis showed that the purity was greater than 98% (Found: C, 64.0; H, 5.9. $C_{13}H_{15}F_3O$ requires: C, 63.9; H, 6.2%). ν_{max} 3020s, 2970s, 1640m, 1270s, 1150s, 965s, 800s, 685s; n.m.r. δ5.62 (7H, singlet with shoulder), 3.70 (2H, quartet, J 8Hz), 3.60 (2H, triplet, J 6Hz), 2.10 (2H, triplet, J 6Hz), 1.72 (2H, multiplet); mass spectrum: m/e 244(35%), 117 (100).

E-1-Cyclooctatetraenylprop-1-ene (121)

The fraction of higher R_f from the above dry column exhibited an n.m.r. spectrum that was consistent with a mixture of olefins. G.l.c. analysis (column C) indicated two components were present (3:2). Preparative g.l.c. (column J) gave a pure sample of E-1-cyclooctatetraenyl-prop-1-ene (121), b.p. 80° (block)/12mm, (Found: C, 91.8; H, 8.3. $C_{11}H_{12}$ requires: C, 91.6; H, 8.4%). ν_{max} 3020s, 2980m, 2960m, 2940m

---

* A sample of the trifluoroethyl ether was also isolated from the solvolysis of (29) in buffered trifluoroethanol.

2855w, 1630w, 1460m, 960s, 800s, 780s, 760s, 695s; n.m.r. δ6.02 (1H, doublet of quartets, J 15.4 and 2.0Hz), 5.67 (7H, singlet), 5.40 (1H, doublet of quartets, J 15.4 and 6Hz), 1.73 (3H, doublets of doublets, J 6 and 2Hz); mass spectrum: m/e 144 (18%), 139 (100).

The other component of the olefin mixture underwent decomposition upon attempted preparative g.l.c.

3-Cyclooctatetraenylpropyl 1,1,1,3,3,3-hexafluoroprop-2-yl ether (122)

To sodium 1,1,1,3,3,3-hexafluoroprop-2-oxide (3.5g; 18.4 mmole), hexamethylphosphoric triamide (20ml) and hexafluoropropan-2-ol (5ml) was added 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (3.20g; 9.21 mmole) with stirring under a nitrogen atmosphere. The temperature was slowly increased to 120° and maintained at 120° for 4 hr. After it had been cooled, the mixture was diluted with 10% aqueous sodium hydroxide and extracted with ether. The ether layer was washed successively with 10% aqueous sodium hydroxide, 5% aqueous hydrochloric acid and 5% aqueous sodium bicarbonate and then dried and concentrated. Dry column chromatography on silica gel using low boiling petroleum as the developing solvent gave the required ether in 48% yield after one distillation, b.p. 110° (block)/12mm. G.l.c. analysis (column C) showed that the purity was greater than 99%, (Found: C, 53.8; H, 4.5. $C_{14}H_{14}F_6O$ requires: C, 53.9; H, 4.5%). ν_{max} 3000s, 2950s, 1645w, 1370s, 1290s, 1220s, 1190s, 1135s, 1100s, 685s; n.m.r. δ5.65 (7H, singlet with shoulder), 3.96 (1H, septet, J 6Hz), 3.86 (2H, triplet, J 6Hz), 2.13 (2H, triplet, J 6Hz), 1.78 (2H, multiplet); mass spectrum: m/e 312 (57%), 117 (100).

Allylcyclooctatetraene (119)

The method described[53] gave the required olefin in 38% yield, b.p. 80-82°/13mm (lit.,[53] 89-90°/20mm).

Bicyclo[6.3.0]undeca-1(8)-en-9-one (124)

The Stobbe condensation[238,239] of cyclooctanone and diethyl succinate followed by hydrolysis and decarboxylation[238,239] gave the unsaturated ketone (124) in 14% yield, b.p. 88-89°/0.5mm (lit.,[239] 96-101°/4mm).

Reduction of bicyclo[6.3.0]undeca-1(8)-en-9-one (124)

(i) The modified Clemmensen reduction of the enone (124) using the general procedure described[53,240] gave an unidentified product, ν_{max} 1740s; n.m.r. δ1.4-2.5ppm.

(ii) Wolff Kischner reduction of the enone (124) using a standard procedure,[325] gave a pale yellow oil which had no carbonyl absorptions in the infrared spectrum. A small portion was purified by preparative g.l.c. (column J) to give a mixture of isomers of bicyclo[6.3.0]undeca-1-ene (125), b.p. 90° (block)/13mm, (Found: C, 88.1; H, 12.1. $C_{11}H_{18}$ requires: C, 87.9; H, 12.1%). ν_{max} 3055m, 2955s, 2860s, 1705m, 1640w, 1460s, 1440s, 800m; n.m.r. δ5.22 (0.8H, broad singlet), δ1.2-2.8 (complex); mass spectrum: m/e 150 (90%), 93 (98), 79 (100).

cis and *trans*-Bicyclo[6.3.0]undecane (126)

The crude mixture from the Wolff Kischner reduction was dissolved in low boiling petroleum and filtered through a column of Sorbsil (15cm). The solution was concentrated, diluted with acetic acid and hydrogenated at room temperature and atmospheric pressure using Adams catalyst. After it had been filtered through celite, the solution was diluted with low boiling petroleum and 10% aqueous sodium hydroxide. The layers were separated and the organic layer was washed successively with 10% aqueous sodium hydroxide and water and then dried and concentrated to give a colorless liquid (24% yield from the enone (124)) after distillation, b.p. 90° (block)/20mm. G.l.c. (column C) indicated two isomers (ca. 3:2). Preparative g.l.c. (column J) and a further distillation gave a sample of the mixture of isomers (126), (Found: C, 86.8; H, 13.0. $C_{11}H_{20}$ requires: C, 86.8; H, 13.2%). ν_{max} 2955s, 2870s, 1460s, 1440s; n.m.r. δ0.9-2.0 (complex); mass spectrum: m/e 152 (80%), 96 (100).

Bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57)

3-Cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) (2.0g; 5.8 mmole) was dissolved in trifluoroethanol* (50ml) containing 2,6-dimethylpyridine (0.68g; 6.3 mmole); the solution was placed in ampoules and dry nitrogen was bubbled through the solution in each ampoule before they were sealed. The ampoules were heated at 100° for 16 hr. in a constant temperature bath and then cooled and opened. The contents of each ampoule were combined and diluted with 5% aqueous

---

* On two occasions, hexafluoropropan-2-ol was used instead of trifluoroethanol; in these instances, however, only polymeric material was obtained.

sodium hydroxide and low boiling petroleum. The layers were separated and the aqueous layer was extracted with low boiling petroleum; the combined organic layers were washed successively with 5% aqueous sodium hydroxide and water and then dried and concentrated to ca. 5ml.* Preparative t.l.c. (dry column chromatography was used on some occasions) on silica gel using low boiling petroleum as the developing solvent separated the olefin (57) from the trifluoroethyl ether (120)** and polymeric material. The tetraene was eluted from the silica gel with the solvent of choice (typically ether, ethyl acetate or carbon tetrachloride) and the solution concentrated to ca. 1-2ml. The solution was used as soon as possible (Accurate mass measurement: m/e 144.0932. $C_{11}H_{12}$ requires: m/e 144.0939). ν_{max} 3030s, 2970s, 2865s, 1710w, 1680w, 1630w, 1455m, 1440w, 1290m, 985m, 910m, 825s, 780s, 765s, 725s; n.m.r. δ6.26 (1H, doublet, J 12Hz), 5.83-5.63 (6H, complex), 3.86 (1H, broad), 2.42-1.59 (4H, complex); ^{13}C n.m.r. ($CDCl_3/CCl_4$ (ca. 1:1)) δ145.09, 141.69, 129.84, 129.60, 127.84, 127.60, 126.99, 124.14, 45.00, 30.79, 30.61; λ_{max}*** 229nm (ε 14,300), shoulder 236 (12,800), 262 (2,500), shoulder 305 (2,200); mass spectrum: m/e 144 (73%), 129 (100).

---

* The sample often polymerizes upon concentration; the tetraene also polymerizes upon standing in ether, light petroleum or carbon tetrachloride either at room temperature or at -15°.

** The n.m.r. spectrum of this ether was identical to that of an authentic sample (see p.182).

*** Since it was necessary to concentrate to dryness to obtain the extinction coefficients, some polymerization may have taken place.

Work described in Chapter 6

4-Cyclooctatetraenylbutanol (152)

Magnesium (2.6g; 0.107 g-atom) and a crystal of iodine were placed in a flask fitted with a condenser, dropping funnel and nitrogen atmosphere. 4-Chlorobut-1-yl tetrahydropyran-2-yl ether (154)* (13.9g; 0.072 mole) in dry tetrahydrofuran (100ml) was placed in the dropping funnel; about 10ml of the solution was added to the flask which was then heated by means of a water bath until initiation occurred. The water bath was removed and the remaining solution was added over 30 min. The mixture was heated under reflux for 1 hr. and then cooled to -10°. Bromocyclooctatetraene[326] (13.1g; 0.071 mole) was added all at once followed by a solution of anhydrous ferric chloride (120mg) in tetrahydrofuran (4ml). The mixture was stirred at 0° for 2 hr. and then poured onto saturated aqueous ammonium chloride and extracted with ether (3 × 700ml). The combined ether extracts were washed with water and concentrated. The dark oil was added to dilute aqueous hydrochloric acid (100ml) and enough tetrahydrofuran was added to give a homogenous solution. After it had been stirred at room temperature for 2 hr., the mixture was carefully neutralized with sodium carbonate. The layers were separated and the aqueous layer was extracted with ether (3 × 500ml); the combined ether layers were washed with water and then dried and concentrated. The dark oil was chromatographed on silica gel (78cm × 2.2cm) and eluted with light petroleum at first and then with gradually increasing proportions of ether in light petroleum. The first fractions yielded biscyclooctatetraene (153) in 11% yield. A sample

---

* Prepared by T. Lawrence.

was recrystallized from ether/light petroleum, m.p. 125-126° (lit.,[327] 125.4-126.5). Later fractions yielded the required alcohol in 42% yield after distillation, b.p. 106-108°/0.2mm (lit.,[53] 77-78°/0.01mm). G.l.c. analysis (column C) showed that the purity was greater than 99% and that it had the same retention time as an authentic sample.*

4-Cyclooctatetraenylbutyl tetrahydropyran-2-yl ether

The above column also yielded 4-cyclooctatetraenylbutyl tetrahydropyran-2-yl ether (0-22% yield), b.p. 126-132°/0.1mm on some occasions; ν_{max} 3020s, 2970s, 2895s, 1640w, 1450m, 1440m, 1350m, 1195m, 1130s, 1120s, 1070s, 1030s; n.m.r. δ5.67 (7H, singlet with shoulder), 4.50 (1H, unresolved triplet), 3.90-3.40 (4H, multiplet), 2.03 (2H, triplet, J 7Hz), 1.9-1.2 (10H, multiplet). This product was hydrolysed and worked up as described above to give 4-cyclooctatetraenylbutanol (152).

4-Cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21)

4-Cyclooctatetraenylbutanol (152) was treated with *p*-nitrobenzenesulphonyl chloride and pyridine as described.[53] One recrystallization from light petroleum followed by dry column chromatography on silica gel (using toluene as the developing solvent) and a further recrystallization from light petroleum gave a 46-56% yield of the required sulphonate, m.p. 61-62° (lit.,[53] 61-62°).**

---

* An authentic sample of the alcohol was obtained in 86% yield from the reduction of 4-cyclooctatetraenylbutyl acetate (67mg) with lithium aluminium hydride; the product was homogeneous by g.l.c. (column C). The acetate was available from earlier work in this department.[53]

** See footnote p. 182.

4-Cyclooctatetraenylbutyl 2,2,2-trifluoroethyl ether (156)

To sodium hydride (0.611g; 12.7 mmole; 50% oil dispersion) and hexamethylphosphoric triamide (20ml), trifluoroethanol (2ml) was added dropwise under a nitrogen atmosphere. After the mixture had been stirred at room temperature for 30 min., 4-cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (2.30g; 6.36 mmole) was added and the mixture was stirred at 130° for 4 hr. The mixture was cooled and diluted with low boiling petroleum and 10% aqueous sodium hydroxide; the layers were separated and the organic layer was washed with water and dried. Dry column chromatography on silica gel using low boiling petroleum gave two fractions; the fraction of higher R_f contained at least 7 components by g.l.c. analysis (column C). The fraction of lower R_f, 0.25g (15% yield), contained the required ether;* the purity was greater than 90% by g.l.c. analysis (column C). Preparative t.l.c. (silica gel) followed by distillation gave a sample of greater than 98% purity, b.p. 130° (block)/30mm, (Found: C, 65.2; H, 6.8. $C_{14}H_{17}F_3O$ requires: C, 65.1; H, 6.6%). ν_{max} 3020s, 2965s, 2885s, 1645w, 1440m, 1270s, 1150s, 965s, 685s, 650s; n.m.r. δ5.70 (7H, singlet with shoulder), 3.76 (2H, quartet, J 9Hz), 3.58 (2H, triplet, J 6Hz), 2.07 (2H, triplet, J 6Hz), 1.92-1.27 (4H, multiplet); mass spectrum: m/e 258 (15%), 115 (100).

1-(2',2',2'-Trifluoroethoxy)bicyclo[6.4.0]dodeca-2,4,6-triene (158)

4-Cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (21) (0.415g; 1.15 mmole) was dissolved in trifluoroethanol (40ml) containing triethylamine (0.174g; 1.73 mmole) and the resulting solution was

---

* A pure sample of the trifluoroethyl ether was also isolated from the solvolysis of (21) in buffered trifluoroethanol (see p.191).

sealed in an ampoule and heated at 80° for 5 hr. After it had been cooled, the ampoule was opened and the contents were concentrated to 5ml by distillation at 90mm (the receiving flask was cooled with dry-ice). The solution was diluted with 5% aqueous sodium hydroxide and ether; the layers were separated and the aqueous phase was extracted with low boiling petroleum. The combined organic layers were washed successively with 10% aqueous sodium hydroxide and water and then dried and concentrated. Preparative t.l.c. on silica gel gave samples of 4-cyclooctatetraenylbutyl 2,2,2-trifluoroethyl ether (156), a mixture of bicyclo[6.4.0]dodeca-2,4,6,8(9)-tetraene (58) and bicyclo[6.4.0]-dodeca-1,3,5,7-tetraene (157) and a mixture (34% yield) of the two isomers of the trifluoroethyl ether (158). G.l.c. analysis (column D) showed that the purity of the mixture of the two isomers (3:2) of (158) was greater than 90%. The n.m.r. spectrum indicated that the two ethers (158) existed in their tricyclic form to a large extent. ν_{max} 3055m, 2960s, 2890s, 1635w, 1580w, 1460m, 1450s, 1275s, 1150s, 1115s, 1100s, 965s, 780s, 715s; n.m.r. δ6.03-5.35 (4.2H, complex), 4.50-3.40 (2.8H, complex, includes 4 overlapping quartets, J 8.5Hz), 3.20-2.83 (1H, complex), 2.67-1.10 (9H, complex); mass spectrum: m/e 258 (1%), 44 (100).

3-(2',2',2'-Trifluoroethoxy)-13,13,14,14-tetracyanotetracyclo-[8.2.2.$0^{2,9}0^{3,8}$]tetradeca-11-ene (160)

The mixture of trifluoroethyl ethers (158) (0.090g; 0.35 mmole) was dissolved in ethyl acetate and tetracyanoethylene* (45mg; 0.35 mmole)

---

* Tetracyanoethylene was sublimed from activated charcoal at 140°/16mm and then resublimed; the activated charcoal was dried at 140°/0.1mm for 4 hr. before use.

was added to the stirred solution under a nitrogen atmosphere. After it had been heated under reflux for 5.5 hr., the mixture was allowed to cool and then concentrated. Preparative t.l.c. on silica gel gave a white solid (0.13g; 96% yield) which was further purified by preparative t.l.c. and then recrystallized from ethanol/water to give a mixture of isomers of (160), (Found: C, 62.3; H, 4.5; N, 14.4. $C_{20}H_{17}F_3N_4O$ requires: C, 62.2; H, 4.4; N, 14.5%). ν_{max} ($CHCl_3$ solution) 3050m, 2975s, 2870m, 2250w, 1620w, 1460m, 1415m, 1275s, 1160s, 1100s, 967s; n.m.r. ($CDCl_3$) δ6.88-6.03 (2H, complex), 4.18-3.30 (5H, complex), 3.17-2.25 (2H, complex), 2.18-1.17 (8H, complex); mass spectrum: m/e 386 (4%), 180 (100).

Bicyclo[6.4.0]dodeca-2,4,6,8(9)-tetraene (58)

(i) From solvolysis

4-Cyclooctatetraenylbutyl *p*-nitrobenzenesulphonate (0.30g; 0.83 mmole) was dissolved in hexafluoropropan-2-ol (15ml) containing triethylamine (0.126g; 1.25 mmole). The solution was placed in an ampoule and dry nitrogen was bubbled through it; the ampoule was sealed and then heated at 40° for 15 hr. The ampoule was opened and the contents were diluted with 10% aqueous sodium hydroxide and low boiling petroleum. The layers were separated and the aqueous phase was extracted with low boiling petroleum; the combined organic extracts were washed successively with 10% aqueous sodium hydroxide (twice), water (twice) and saturated aqueous sodium chloride. The solution was dried and concentrated* to ca. 1ml and then diluted with

---

* As for the tetraene (57), this tetraene i.e. (58) is prone to polymerization (see footnote p.187).

deuterochloroform (2ml) and concentrated to ca. 0.5ml. The solution was diluted with deuterochloroform and concentrated to 0.5ml a further two times. The yield of tetracyanoethylene adduct (see p.196) indicated that the yield of tetraene (58) was greater than or equal to 97%. ν_{max} 3030m, 2960s, 2890m, 1635w, 1580w, 1445m, 1270s, 1150s, 965m, 805m, 715m; n.m.r. ($CDCl_3$) δ6.13 (1H, doublet, J 12Hz), 6.00-5.50 (6H, complex), 3.76 (1H, broad), 2.26-1.50 (6H, complex); ^{13}C n.m.r. δ142.68, 138.20, 137.83, 128.86, 128.38, 127.89, 126.56, 121.83, 35.40, 27.40, 25.46, 17.94.

(ii) From the Wittig reaction

4-(2-Oxocycloocta-3,5,7-trienyl)butyltriphenylphosphonium iodide (161)* (5.06g; 8.98 mmole) was dissolved in dry dimethylsulphoxide (20ml) and the solution was added with stirring under a nitrogen atmosphere to potassium methylsulphinylmethide** in dimethylsulphoxide. The mixture immediately became dark red in colour; the colour darkened first to dark green and then black after heating at 100° for 0.5 hr. After it had been cooled, the reaction mixture was diluted with low boiling petroleum and water. The layers were separated and the aqueous layer was washed with low boiling petroleum. The combined organic layers were washed with water (twice) and then dried and concentrated to ca. 1ml. Dry column chromatography on silica gel gave the required tetraene in 24% yield (based on the yield of its

---

* The phosphonium salt was prepared by R. Stafford; the procedure used was that of R.D. Wagner[284] except that acetonitrile was found to be a better solvent for the preparation of the phosphonium salt.

** Prepared by stirring a mixture of potassium hydride (0.72g; 9.0 mmole; 50% oil dispersion) and dimethylsulphoxide (10ml) at room temperature under a nitrogen atmosphere for 1 hr.

tetracyanoethylene adduct). Accurate mass measurement; found: m/e 158.1095. $C_{12}H_{14}$ requires: 158.1095. Mass spectrum: m/e 158 (9%), 44 (100). The ^{1}H n.m.r. spectrum was identical to that of the tetraene prepared *via* solvolysis.

Work described in Chapter 7

9,9,10,10-Tetracyanotricyclo[6.5.0.$0^{2,11}$]trideca-2,4,6-triene (173)

A solution of bicyclo[6.3.0]undeca-2,4,6,8(9)-tetraene (57) in ethyl acetate obtained from the solvolysis of 3-cyclooctatetraenylpropyl *p*-nitrobenzenesulphonate (29) (0.67g) in buffered trifluoroethanol (see above) was concentrated to ca. 5ml. Tetracyanoethylene* (0.15g; 1.2 mmole) was added to the stirred solution under a nitrogen atmosphere. The colour of the solution immediately changed to a deep blue-green but the colour disappeared again upon warming. The solution was heated under reflux for 10 mins. If the work-up procedure was carried out at this stage the product was contaminated with a pink colour; this pink impurity did not affect the m.p. or n.m.r spectrum and it could easily be removed by washing the crystals with cold ethanol. The reaction mixture was heated under reflux for a further 2 hr. After cooling, the reaction mixture was chromatographed (preparative t.l.c.) on silica gel using 40% ether in low boiling petroleum as the developing solvent. The resulting white solid (31% from the sulphonate ester (29))** was recrystallized from ethanol/water, m.p. 203-203.5°, (Found: C, 74.7; H, 4.2; N, 20.3. $C_{17}H_{12}N_4$ requires: C, 75.0; H, 4.4; N, 20.6%). N.m.r. ($CDCl_3$) δ6.40-5.93 (5H, complex), 3.82 (1H, multiplet), 3.52 (1H, multiplet), 3.25 (1H, multiplet), 2.60-1.93 (4H, multiplet); n.m.r. (CD_3COCD_3) δ6.53-5.9 (4H, complex), 4.25 (1H, multiplet), 4.00 (1H, multiplet), 3.33 (1H, multiplet), 2.56-1.82 (multiplet); ^{13}C n.m.r. δ140.35, 130.82, 129.24, 127.90,

---

* See footnote p. 191.

** See footnote p. 126.

126.02, 124.56, 52.65, 51.74, 37.96, 25.39, 23.38; mass spectrum: m/e 272 (10%), 144 (75), 129 (100); λ_{max} 212nm (ε 10,400), 264 (3,100).

Treatment of bicyclo[6.4.0]dodeca-2,4,6,8(9)-tetraene (58) with tetracyanoethylene

To the tetraene (58) in ethyl acetate, tetracyanoethylene* (excess) was added with stirring under nitrogen. The solution immediately became green-violet in colour; this colour changed to brown when the solution was heated. The mixture was heated under reflux for 1 hr. and then allowed to cool. Chromatography on silica gel gave a white solid in 97% yield (from the sulphonate (21)), m.p. 185-186° after recrystallization from ethanol/water, (Found: C, 75.4; H, 4.9; N, 19.4. $C_{18}H_{14}N_4$ requires: C, 75.5; H, 4.9; N, 19.6%). ^{13}C N.m.r. indicated that 3 adducts were present**; h.p.l.c. gave two peaks (3:2) using the ultraviolet detector at 280nm. The mixture (446mg) was separated by h.p.l.c. (15% ether in hexane) to give two fractions:

(i) 7,7,8,8-Tetracyanotetracyclo[7.5.0.0^{1,6}0^{2,14}]tetradeca-10,12-diene (176)

The fraction of longer retention time was shown to contain one adduct; this adduct is tentatively identified as (176). The yield obtained was 146mg; it was recrystallized from chloroform/hexane to give m.p. 174-175°, (Found: C, 75.3; H, 5.0. $C_{18}H_{14}N_4$ requires: C, 75.5; H, 4.9%). N.m.r. ($CDCl_3$, 80MHz) δ6.43-6.06 (2H, doublet of

---

* See footnote p. 191.

** The same 3 adducts were obtained when the tetraene (58) was prepared *via* solvolysis or *via* the Wittig reaction.

doublets, J 7.5 and 11.5Hz), 5.81-5.38 (2H, complex), 3.93 (1H, doublet, J 7.6Hz), 2.63-2.31 (1H, complex), 2.25-0.7 (8H, complex); n.m.r. (CD_3CN) δ6.38-5.95 (2H, multiplet), 5.75-5.32 (2H, multiplet), 4.10 (1H, doublet, J 7.5Hz), 2.93-2.57 (1H, multiplet), 2.22-1.1 (complex); n.m.r. (CD_3COCD_3) δ6.37-5.98 (2H, multiplet), 5.78-5.28 (2H, multiplet), 4.30 (1H, doublet, J 8Hz), 3.17-2.80 (1H, multiplet), 2.23-0.8 (complex); ^{13}C n.m.r. δ135.07 (doublet, J (^{13}C-^{1}H) 163Hz), 134.82 (doublet, J 163Hz), 122.07 (doublet, J 163Hz), 118.18 (doublet, J 163Hz), 59.33 (doublet, J 125Hz), 52.96 (doublet, J 125Hz), 49.31 (singlet), 27.69 (doublet, J 175Hz), 26.96 (doublet, J 175Hz), 20.65 (triplet, J 125Hz), 20.35 (2 carbon atoms, triplet, J 125 Hz); λ_{max} 280nm (ε 4,000).

(ii) 9,9,10,10-tetracyanotricyclo[6.6.0.$0^{2,11}$]tetradeca-2,4,6-triene (182)

The second fraction obtained from the preparative h.p.l.c. above (218mg) gave only one peak by h.p.l.c.; it was recrystallized from ethanol/water to give m.p. 181-183°, (Found: C, 75.1; H, 5.1. $C_{18}H_{14}N_4$ requires: C, 75.5; H, 4.9). N.m.r. ($CDCl_3$) δ6.50-5.3 (4.3H, complex), 4.2-3.0 (3H, complex), 2.6-0.7 (6.7H, complex); ^{13}C n.m.r. indicates two compounds are present; the more intense resonances (δ135.13, 130.51, 130.21, 127.90, 127.66 (2 carbon atoms?), 52.11, 48.04, 30.24, 25.02, 24.17, 18.58) are tentatively assigned to structure (182). The less intense resonances are: δ126.32, 125.47, 125.23, 125.05, 53.69, 46.10, 41.66, 40.81, 34.19, 22.53, 18.22, 16.65. λ_{max} 210nm (ε 13,600), 265 (3,400). Recrystallization from ether/hexane gave m.p. 189.5-190.5°.

13,13,14,14-Tetracyanotetracyclo[8.2.2.$0^{2,9}0^{3,8}$]tetradeca-3(8),11-diene (183)

Treatment of bicyclo[6.4.0]dodeca-1,3,5,7-tetraene (157) with tetracyanoethylene as described[328] gave the required adduct, m.p. 239.5-240.5° (lit.,[328] 237-239° dec.) after purification by preparative t.l.c. on silica gel and one recrystallization from chloroform/light petroleum; ^{13}C n.m.r. δ145.15 (low intensity), 135.13, 129.90, 43.79, 37.96, 23.26, 22.29.

REFERENCES

REFERENCES

1. G.E. Gream, Aust. J. Chem., 25, 1051 (1972).

2. G.E. Gream, A.K. Serelis, T.I. Stoneman, Aust. J. Chem., 27, 1711 (1974).

3. S. Winstein, P. Carter, J. Amer. Chem. Soc., 83, 4485 (1961).

4. J.M. Harris, Prog. Phys. Org. Chem., 11, 89 (1974).

5. S. Winstein, B. Appel, R. Baker, A. Diaz, Chem. Soc. Special Publ. No. 19, 109 (1965).

6. D.J. Raber, J.M. Harris, P.v.R. Schleyer, "Ions and Ion Pairs in Organic Reactions", Vol. 2, p. 247-374, Ed. M. Szwarc (Wiley, N.Y.) 1974.

7. D.J. Raber, J.M. Harris, R.E. Hall, P.v.R. Schleyer, J. Amer. Chem. Soc., 93, 4821 (1971).

8. V.J. Shiner, Jr., R.D. Fisher, J. Amer. Chem. Soc., 93, 2553 (1971).

9. B. Capon, S.P. McManus, "Neighbouring Group Participation", Vol. 1 (Plenum Press, N.Y.) 1976.

10. S. Winstein, C.R. Lindegren, H. Marshall, L.L. Ingraham, J. Amer. Chem. Soc., 75, 147 (1953).

11. M.L. Bender, J. Amer. Chem. Soc., 79, 1258 (1957).

12. A. Streitwieser, Jr., "Solvolytic Displacement Reactions" (McGraw-Hill, N.Y.) 1962.

13. M. Hanack, H.J. Schneider, Angew. Chem. Int. Edn., 6, 666 (1967).

14. M. Hanack, H.J. Schneider, Fortschr. Chem. Forsch., 8, 554 (1967).

15. G.A. Olah, P.v.R. Schleyer (Eds), "Carbonium Ions", Vol. 3, (Wiley-Interscience, N.Y.), 1972, (a) P.R. Story, B.C. Clark,Jr., p. 1007 (b) C.J. Lancelot, D.J. Cram, P.v.R. Schleyer, p. 1347.

16. B. Capon, Quart. Rev., 18, 45 (1964).

17. B. Capon, C.W. Rees (1965-1972), M.J. Perkins (1965-1967; 1973-1976), A.R. Butler (1973-1976), A.C. Knipe, W.E. Watts (1977), (Eds.), "Organic Reaction Mechanisms", 1965-1977 (Interscience, N.Y.).

18. I. Dragutan, Studii Si Cercetari de Chimie, 22, 1977 (1974).

19. M. Hanack, Angew. Chem. Int. Ed., 17, 333 (1978).

20. P.B.D.De la Mare, "Molecular Rearrangements", Part 1, ch. 2, Ed. P.de Mayo (Interscience, N.Y.), 1963.

21. N.C. Deno, "Carbonium Ions", Vol. 2, Ed. G.A. Olah, P.v.R. Schleyer, p. 783 (Wiley-Interscience, N.Y.), 1970.

22. L.A. Paquette, K.A. Henzel, J. Amer. Chem. Soc., 95, 2724 (1973).

23. W. Kitching, K.A. Henzel, L.A. Paquette, J. Amer. Chem. Soc., 97, 4643 (1975).

24. D.A. daRoza, L.J. Andrews, R.M. Keefer, J. Amer. Chem. Soc., 95, 7003 (1973).

25. J.B. Lambert, S.I. Featherman, Tet. Lett., 2663 (1975).

26. J.B. Lambert, S.I. Featherman, J. Amer. Chem. Soc., 99, 1542 (1977).

27. L.A. Paquette, K.A. Henzel, J. Amer. Chem. Soc., 95, 2726 (1973).

28. C.W. Shoppee, J. Chem. Soc., 1147 (1946).

29. A.C. Cope, P.E. Peterson, J. Amer. Chem. Soc., 81, 1643 (1959).

30. W.D. Closson, G.T. Kwiatkowski, Tet., 21, 2779 (1965).

31. B. Fraser-Reid, Accts. Chem. Res., 8, 192 (1975).

32. S. Winstein, R. Adams, J. Amer. Chem. Soc., 70, 838 (1948).

33. J.B. Rogan, J. Org. Chem., 27, 3910 (1962).

34. F.L. Schadt, P.v.R. Schleyer, J. Amer. Chem. Soc., 95, 7860 (1973).

35. D.S. Noyce, R.L. Castenson, J. Amer. Chem. Soc., 95, 1247 (1973).

36. D.S. Noyce, R.L. Castenson, D.A. Meyers, J. Org. Chem., 37, 4222 (1972).

37. F.L. Schadt, C.J. Lancelot, P.v.R. Schleyer, J. Amer. Chem. Soc., 100, 228 (1978).

38. J.E. Nordlander, W.G. Deadman, J. Amer. Chem. Soc., 90, 1590 (1968).

39. A. Diaz, I. Lazdins, S. Winstein, J. Amer. Chem. Soc., 90, 6546 (1968).

40. A.F. Diaz, S. Winstein, J. Amer. Chem. Soc., 91, 4300 (1969).

41. J.E. Nordlander, W.J. Kelly, J. Amer. Chem. Soc., 91, 996 (1969).

42. J.A. Berson, D.S. Donald, W.J. Libbey, J. Amer. Chem. Soc., 91, 5580 (1969).

43. S. Winstein, R. Heck, J. Amer. Chem. Soc., 78, 4801 (1956).

44. C.C. Lee, G.P. Slater, J.W.T. Spinks, Can. J. Chem., 35, 1417 (1957).

45. C.C. Lee, R.Tkachuk, G.P. Slater, Tet., 7, 206 (1959).

46. W.H. Saunders, Jr., S. Asperger, D.H. Edison, J. Amer. Chem. Soc., 80, 2421 (1958).

47. J.L. Coke, F.E. McFarlane, M.C. Mourning, M.G. Jones, J. Amer. Chem. Soc., 91, 1154 (1969).

48. C.J. Lancelot, P.v.R. Schleyer, J. Amer. Chem. Soc., 91, 4291 (1969).

49. C.J. Lancelot, J.J. Harper, P.v.R. Schleyer, J. Amer. Chem. Soc., 91, 4294 (1969).

50. C.J. Lancelot, P.v.R. Schleyer, J. Amer. Chem. Soc., 91, 4296 (1969).

51. P.v.R. Schleyer, C.J. Lancelot, J. Amer. Chem. Soc., 91, 4297 (1969).

52. T. Ando, J. Yamawaki, Y. Saito, Bull. Chem. Soc. Japan, 51, 219 (1978).

53. G.E. Gream, M. Mular, Aust. J. Chem., 28, 2227 (1975).

54. H.L. Goering, W.D. Closson, J. Amer. Chem. Soc., 83, 3511 (1961).

55. R.K. Bly, R.S. Bly, J. Org. Chem., 31, 1577 (1966).

56. J.A. Berson, J.J. Gajewski, D.S. Donald, J. Amer. Chem. Soc., 91, 5550 (1969).

57. P.D. Bartlett, Annalen, 653, 45 (1962).

58. W.S. Johnson, D.M. Bailey, R. Owyang, R.A. Bell, B. Jaques, J.K. Crandall, J. Amer. Chem. Soc., 86, 1959 (1964).

59. K.B. Becker, A.F. Boschung, C.A. Grob, Helv. Chim. Acta., 56, 2733 (1973).

60. P.D. Bartlett, W.D. Closson, T.J. Cogdell, J. Amer. Chem. Soc., 87, 1308 (1965).

61. W.S. Johnson, R. Owyang, J. Amer. Chem. Soc., 86, 5593 (1964).

62. H.L. Goering, H.H. Espy, W.D. Closson, J. Amer. Chem. Soc., 81, 329 (1959).

63. T.C. Clarke, R.G. Bergman, J. Amer. Chem. Soc., 96, 7934 (1974).

64. E. Cioranescu, M. Banciu, R. Jelescu, M. Rentzea, M. Elian, C.D. Nenitzescu, Tet. Lett., 1871 (1969).

65. E. Cioranescu, M. Banciu, R. Jelescu, M. Rentzea, M. Elian, C.D. Nenitzescu, Rev. Roum. Chim., 14, 911 (1969).

66. M. Voica, F. Badea, Rev. Roum. Chim., 14, 929 (1969).

67. M. Banciu, F. Badea, R. Jelescu, E. Cioranescu, Rev. Roum. Chim., 20, 121 (1975).

68. T.M. Cunningham, K.H. Overton, J.C.S. Perkin I, 2140 (1975).

69. A.C. Cope, D.L. Neady, P. Scheiner, G. Wood, J. Amer. Chem. Soc., 87, 3130 (1965).

70. P.D. Bartlett, W.S. Trahanovsky, D.A. Bolon, G.H. Schmid, J. Amer. Chem. Soc., 87, 1314 (1965).

71. L.A. Spurlock, K.P. Clark, J. Amer. Chem. Soc., 92, 3829 (1970).

72. L.A. Spurlock, K.P. Clark, J. Amer. Chem. Soc., 94, 5349 (1972).

73. G.D. Sargent, T.E. McLaughlin, Tet. Lett., 4359 (1970).

74. W.S. Trahanovsky, M.P. Doyle, Tet. Lett., 2155 (1968).

75. H. Felkin, C. Lion, Tet., 27, 1403 (1971).

76. H. Felkin, C. Lion, J.C.S. Chem. Comm., 60 (1968).

77. E. Cioranescu, A. Bucur, M. Elian, C.D. Nenitzescu, Rev. Roum. Chim., 10, 149 (1965).

78. E. Cioranescu, A. Bucur, M. Elian, M. Banciu, M. Voicu, C.D. Nenitzescu, Rev. Roum. Chim., 10, 161 (1965).

79. E. Cioranescu, A. Bucur, F. Badea, M. Rentzea, C.D. Nenitzescu, Tet. Lett., 1867 (1969).

80. E. Cioranescu, A. Bucur, M. Elian, M. Banciu, M. Voicu, C.D. Nenitzescu, Tet. Lett., 3835 (1964).

81. P.D. Bartlett, E.M. Nicholson, R. Owyang, Tet. suppl. part II, 399 (1966).

82. W. Kraus, W. Rothenwöhrer, W. Kaiser, M. Hanack, Tet. Lett., 1705 (1966).

83. M. Hanack, W. Kraus, W. Rothenwöhrer, W. Kaiser, G. Wentrup, Annalen, 703, 44 (1967).

84. S. Winstein, R.L. Hansen, Tet. Lett., no. 25, 4 (1960).

85. P.E. Peterson, R.J. Kamat, J. Amer. Chem. Soc., 91, 4521 (1969).

86. W.S. Trahanovsky, M.P. Doyle, J. Amer. Chem. Soc., 89, 4867 (1967).

87. H. Felkin, C. Lion, Tet., 27, 1387 (1971).

88. H. Felkin, C. Lion, Tet., 27, 1375 (1971).

89. H.C. Brown, E.N. Peters, M. Ravindranathan, J. Amer. Chem. Soc., 97, 7449 (1975).

90. H.C. Brown, E.N. Peters, M. Ravindranathan, J. Amer. Chem. Soc., 97, 2900 (1975).

91. G. Le Ny, C.r. hebd. Seanc. Acad. Sci. Paris, 251, 1526 (1960).

92. R.G. Lawton, J. Amer. Chem. Soc., 83, 2399 (1961).

93. G.E. Gream, A.K. Serelis, Aust. J. Chem., 27, 629 (1974).

94. W.D. Closson, D. Gray, J. Org. Chem., 35, 3737 (1970).

95. W.D. Closson, G.T. Kwiatkowski, J. Amer. Chem. Soc., 86, 1887 (1964).

96. C. Chuit, Tet., 28, 4815 (1972).

97. C. Chuit, Tet., 28, 4797 (1972).

98. C. Chuit, H. Felkin, G. Le Ny, C. Lion, L. Prunier, Tet., 28, 4787 (1972).

99. R.S. Bly, R.K. Bly, A.O. Bedenbaugh, O.R. Vail, J. Amer. Chem Soc., 89, 880 (1967).

100. K.B. Becker, A.F. Boschung, M. Giesel, C.A. Grob, Helv. Chim. Acta., 56, 2747 (1973).

101. P.D. Bartlett, G.D. Sargent, J. Amer. Chem. Soc., 87, 1297 (1965).

102. P.D. Bartlett, S. Bank, R.J. Crawford, G.H. Schmid, J. Amer. Chem. Soc., 87, 1288 (1965).

103. P.D. Bartlett, S. Bank, J. Amer. Chem. Soc., 83, 2591 (1961).

104. S.A. Roman, W.D. Closson, J. Amer. Chem. Soc., 91, 1701 (1969).

105. H.L. Goering, A.C. Olson, H.H. Espy, J. Amer. Chem. Soc., 78, 5371 (1956).

106. P.G. Gassman, J.L. Marshall, J. Amer. Chem. Soc., 88, 2599 (1966).

107. J.L. Marshall, Tet. Lett., 753 (1971).

108. G.D. Sargent, Quart. Rev., 20, 301 (1966).

109. R. Heck, S. Winstein, J. Amer. Chem. Soc., 79, 3105 (1957).

110. R. Heck, S. Winstein, J. Amer. Chem. Soc., 79, 3114 (1957).

111. S. Winstein, R.F. Heck, J. Org. Chem., 37, 825 (1972).

112. L.M. Jackman, V.R. Haddon, J. Amer. Chem. Soc., 96, 5130 (1974).

113. M. Gates, D.L. Frank, W.C.v. Felton, J. Amer. Chem. Soc., 96, 5138 (1974).

114. C. Chuit, F. Colaard, M. Felkin, J.C.S. Chem. Comm., 118 (1966).

115. G.E. Gream, M.H. Laffer, A.K. Serelis, Tet. Lett., 4713 (1975).

116. G.E. Gream, M.H. Laffer, A.K. Serelis, Aust. J. Chem., 31, 835 (1978).

117. G.E. Gream, A.K. Serelis, Aust. J. Chem., 31, 863 (1978).

118. P.J. Stang, T.E. Dueber, J. Amer. Chem. Soc., 95, 2683 (1973).

119. R.B. Woodward, K. Bloch, J. Amer. Chem. Soc., 75, 2023 (1953).

120. W.G. Dauben, S. Abraham, S. Hotta, I.L. Chaikoff, H.L. Bradlow, A.H. Soloway, J. Amer. Chem. Soc., 75, 3038 (1953).

121. A. Eschenmoser, L. Ruzicka, O. Jeger, D. Arigoni, Helv. Chim. Acta., 38, 1890 (1955).

122. G. Stork, A.W. Burgstahler, J. Amer. Chem. Soc., 77, 5068 (1955).

123. W.S. Johnson, Accts. Chem. Res., 1, 1 (1968).

124. E.E. van Tamelen, Accts. Chem. Res., 1, 111 (1968).

125. W.S. Johnson, Angew. Chem. Int. Ed., 15, 9 (1976).

126. F. Freeman, Chem. Rev., 75, 439 (1975).

127. G.H. Schmid, T.T. Tidwell, J. Org. Chem., 43, 460 (1978).

128. D. Swern, J. Amer. Chem. Soc., 69, 1692 (1947).

129. D. Swern, Chem. Rev., 45, 1 (1949).

130. G.H. Schmid, V.J. Nowlan, Can. J. Chem., 54, 695 (1976).

131. G.H. Schmid, D.G. Garratt, Can. J. Chem., 51, 2463 (1973).

132. G.H. Schmid, C.L. Dean, D.G. Garratt, Can. J. Chem., 54, 1253 (1976).

133. C.K. Ingold, E.H. Ingold, J. Chem. Soc., 2354 (1931).

134. S.V. Anantakrishnan, C.K. Ingold, J. Chem. Soc., 984 (1935).

135. S.V. Anantakrishnan, C.K. Ingold, J. Chem. Soc., 1396 (1935).

136. J.E. Dubois, P. Alcais, G. Barbier, E. Bienvenue-Goetz, Bull. Soc. Chim. Fr., 2113 (1966).

137. M. Charton, B.I. Charton, J. Org. Chem., 38, 1631 (1973).

138. J.E. Dubois, G. Mouvier, Tet. Lett., 1325 (1963).

139. P.S. Skell, A.Y. Garner, J. Amer. Chem. Soc., 78, 5430 (1956).

140. W.K. Chwang, V.J. Nowlan, T.T. Tidwell, J. Amer. Chem. Soc., 99, 7233 (1977).

141. V.J. Nowlan, T.T. Tidwell, Accts. Chem. Res., 10, 252 (1977).

142. K. Oyama, T.T. Tidwell, J. Amer. Chem. Soc., 98, 947 (1976).

143. W.S. Johnson, L.A. Bunes, J. Amer. Chem. Soc., 98, 5597 (1976).

144. W.S. Johnson, S. Escher, B.W. Metcalf, J. Amer. Chem. Soc., 98, 1039 (1976).

145. W.S. Johnson, G.E. Dubois, J. Amer. Chem. Soc., 98, 1038 (1976).

146. F.C. Uhle, J. Org. Chem., 31, 4193 (1966).

147. T.W. Bentley, P.v.R. Schleyer, Adv. Phys. Org. Chem., 14, 1 (1977).

148. D.J. Raber, W.C. Neal, Jr., M.D. Dukes, J.M. Harris, D.L. Mount, J. Amer. Chem. Soc., 100, 8137 (1978).

149. P.v.R. Schleyer, J.L. Fry, L.K.M. Lam, C.J. Lancelot, J. Amer. Chem. Soc., 92, 2542 (1970).

150. T.W. Bentley, P.v.R. Schleyer, J. Amer. Chem. Soc., 98, 7658 (1976).

151. F.L. Schadt, T.W. Bentley, P.v.R. Schleyer, J. Amer. Chem. Soc., 98, 7667 (1976).

152. S. Winstein, A.H. Fainberg, J. Amer. Chem. Soc., 79, 5937 (1957).

153. E. Grunwald, S. Winstein, J. Amer. Chem. Soc., 70, 846 (1948).

154. V.J. Shiner, Jr., W. Dowd, R.D. Fisher, S.R. Hartshorn, M.A. Kessick, L. Milakofsky, M.W. Rapp, J. Amer. Chem. Soc., 91, 4838 (1969).

155. J.M. Harris, D.J. Raber, W.C. Neal, Jr., M.D. Dukes, Tet. Lett., 2331 (1974).

156. Z. Rappoport, J. Kaspi, J. Amer. Chem. Soc., 96, 586 (1974).

157. Z. Rappoport, J. Kaspi, J. Amer. Chem. Soc., 96, 4518 (1974).

158. J.M. Harris, D.L. Mount, M.R. Smith, W.C. Neal, Jr., M.D. Dukes, D.J. Raber, J. Amer. Chem. Soc., 100, 8147 (1978).

159. D.J. Raber, R.C. Bingham, J.M. Harris, J.L. Fry, P.v.R. Schleyer, J. Amer. Chem. Soc., 92, 5977 (1970).

160. D.E. Sunko, I. Szele, M. Tomic, Tet. Lett., 1827 (1972).

161. D.E. Sunko, I. Szele, Tet. Lett., 3617 (1972).

162. T.W. Bentley, F.L. Schadt, P.v.R. Schleyer, J. Amer. Chem. Soc., 94, 992 (1972).

163. D.D. Roberts, J. Org. Chem., 39, 1265 (1974).

164. W.G. Dauben, J.L. Chitwood, J. Amer. Chem. Soc., 90, 6876 (1968).

165. I.L. Reich, A. Diaz, S. Winstein, J. Amer. Chem. Soc., 91, 5635 (1969).

166. A.L. Henne, C.J. Fox, J. Amer. Chem. Soc., 73, 2323 (1951).

167. F.L. Scott, Chem. and Ind., 224 (1959).

168. F.L. Schadt, P.v.R. Schleyer, Tet. Lett., 2335 (1974).

169. M.D. Bentley, J.A. Lacadie, Tet. Lett., 741 (1971).

170. G.A. Dafforn, A. Streitwieser, Jr., Tet. Lett., 3159 (1970).

171. R.C. Seib, V.J. Shiner, Jr., V. Sendijarevic, K. Humski, J. Amer. Chem. Soc., 100, 8133 (1978).

172. D.J. Raber, M.D. Dukes, J. Gregory, Tet. Lett., 667 (1974).

173. M.J. Chandy, M. Hanack, Tet. Lett., 4515 (1975).

174. J.R. Hazen, J. Org. Chem., 35, 973 (1970).

175. D.D. Roberts, C.H. Wu, J. Org. Chem., 39, 3937 (1974).

176. K. Humski, V. Sendijarevic, V.J. Shiner, Jr., J. Amer. Chem. Soc., 98, 2865 (1976).

177. J.M. Harris, D.L. Mount, M.R. Smith, S.P. McManus, J. Amer. Chem. Soc., 99, 1283 (1977).

178. R. Partch, D. Margosian, J. Amer. Chem. Soc., 98, 6746 (1976).

179. I.M. Takakis, Y.E. Rhodes, Tet. Lett., 2475 (1978).

180. W.D. Pfeifer, C.A. Bahn, P.v.R. Schleyer, S. Bocher, C.E. Harding, K. Hummel, M. Hanack, P.J. Stang, J. Amer. Chem. Soc., 93, 1513 (1971).

181. I.R. Subramanian, M. Hanack, L.W.K. Chang, M.A. Imhoff, P.v.R. Schleyer, F.Effenberger, W. Kurtz, P.J. Stang, T.E. Dueber, J. Org. Chem., 41, 4099 (1976).

182. J. Salaün, J. Org. Chem., 42, 28 (1977).

183. D.D. Roberts, J. Org. Chem., 37, 1510 (1972).

184. D.D. Roberts, J. Org. Chem., 36, 1913 (1971).

185. T. Ando, S. Tsukamato, Tet. Lett., 2775 (1977).

186. Y.E. Rhodes, I.M. Takakis, P.E. Schueler, R.A. Weiss, Tet. Lett., 2479 (1978).

187. N.H. Anderson, Y. Yamamoto, A.D. Denniston, Tet. Lett., 4547 (1975).

188. C.W. Roberts, E.T. McBee, C.E. Hathaway, J. Org. Chem., 21, 1369 (1956).

189. P. Ballinger, F.A. Long, J. Amer. Chem. Soc., 81, 1050 (1959).

190. B.L. Dyatkin, E.P. Mochalina, I.L. Knunyants, Tet., 21, 2991 (1965).

191. W.J. Middleton, R.V. Lindsey, Jr., J. Amer. Chem. Soc., 86, 4948 (1964).

192. T.I. Stoneman, M.Sc. Thesis, The University of Adelaide, 1970.

193. P.H. Ferber, B.Sc.(Hons.) Thesis, The University of Adelaide, 1974.

194. J.S. McKenzie, B.Sc.(Hons.) Thesis, The University of Adelaide, 1972.

195. N.B. Lorette, W.L. Howard, J. Org. Chem., 25, 521 (1960).

196. N.B. Lorette, W.L. Howard, Org. Syn., 42, 34 (1962).

197. N.B. Lorette, W.L. Howard, J. Org. Chem., 26, 3114 (1961).

198. N.B. Lorette, W.L. Howard, Org. Syn., 42, 14 (1962).

199. I.J. Borowitz, G. Gonis, R. Kelsey, R. Rapp, G.J. Williams, J. Org. Chem., 31, 3032 (1966).

200. L.W. Deady, R.D. Topsom, J. Vaughan, J. Chem. Soc., 2094 (1963).

201. H.C. Brown, M.H. Rei, J. Amer. Chem. Soc., 91, 5646 (1969).

202. v.W. Hückel, D. Maucher, O. Fechtig, J. Kurz, M. Heinzel, A. Hubele, Annalen, 645, 115 (1961).

203. F.G. Riddell, Quart. Rev., 21, 364 (1967).

204. C. Romers, C. Altona, H.R. Buys, E. Havinga, Topics in Stereochemistry, 4, 39 (1969).

205. B. Capon, Chem. Rev., 69, 407 (1969).

206. E.L. Eliel, Accts. Chem. Res., 3, 1 (1970).

207. J. Dale, Tet., 30, 1683 (1974).

208. J. Colonge, J. Dreux, M. Thiers, Bull. Soc. Chim. Fr., 1459 (1959).

209. R.K. Boeckman, Jr., K.J. Bruza, G.R. Heinrich, J. Amer. Chem. Soc., 100, 7101 (1978).

210. H.O. House, W.V. Phillips, T.S.B. Sayer, C.C. Yau, J. Org. Chem., 43, 700 (1978).

211. S.J. Etheridge, J. Org. Chem., 31, 1991 (1966).

212. E. Taskinen, Tet., 34, 433 (1978).

213. E. Taskinen, M.L. Pentikäinen, Tet., 34, 2365 (1978).

214. N.B. Chapman, W.E. Laird, Chem. and Ind., 20 (1954).

215. S. Winstein, E. Allred, R. Heck, R. Glick, Tet., 3, 1 (1968).

216. L.A. Paquette, M.K. Scott, J. Amer. Chem. Soc., 94, 6760 (1972).

217. P.G. Gassman, J.L. Marshall, J.G. Macmillan, J. Amer. Chem. Soc., 95, 6319 (1973).

218. M.A. Hussein, D.J. Millen, G.W. Mines, J.C.S. Faraday II, 72, 686 (1976).

219. A.J. Barnes, H.E. Hallan, D. Jones, J.C.S. Faraday II, 70, 422 (1974).

220. A. Kivinen, J. Murto, L. Kilpi, Suomen Kemistilehti B, 40, 301 (1967).

221. R.W. Taft, D. Gurka, L. Joris, P.v.R. Schleyer, J.W. Rakshys, J. Amer. Chem. Soc., 91, 4801 (1969).

222. See reference 191.

223. A. Fratiello, R.E. Schuster, G.A. Vidulich, J. Bragin, D. Liu, J. Amer. Chem. Soc., 95, 631 (1978).

224. K.F. Purcell, J.A. Stikeleather, S.D. Brunk, J. Amer. Chem. Soc., 91, 4019 (1969).

225. D. Taub, N.N. Girotra, R.D. Hoffsommer, C.H. Kuo, H.L. Slates, S. Weber, N.L. Wendler, Tet., 24, 2443 (1968).

226. H.C. Brown, G. Zweifel, J. Amer. Chem. Soc., 83, 1241 (1961).

227. H.C. Brown, A.W. Moerikofer, J. Amer. Chem. Soc., 85, 2063 (1963).

228. T. Ando, Y. Saito, J. Yamawaki, H. Morisaki, M. Sawada, Y. Yukawa, J. Org. Chem., 39, 2465 (1974).

229. D.D. Perrin, W.L.F. Armarego, D.R. Perrin, "Purification of Laboratory Chemicals", p. 143 (Pergamon Press), 1966.

230. R.K. Boeckman, Jr., K.J. Bruza, Tet. Lett., 4187 (1977).

231. I.M. Downie, J.B. Holmes, J.B. Lee, Chem. and Ind., 900 (1966).

232. R.S. Tipson, J. Org. Chem., 9, 235 (1944).

233. L.E. Schniepp, H.H. Geller, J. Amer. Chem. Soc., 67, 54 (1945).

234. P.E. Peterson, D.M. Chevli, J. Org. Chem., 39, 3684 (1974).

235. J.E. Baldwin, J.C.S. Chem. Comm., 734 (1976).

236. J.E. Baldwin, J.C.S. Chem. Comm., 736 (1976).

237. C.D. Hurd, H.T. Bollman, J. Amer. Chem. Soc., 55, 699 (1933).

238. K. Bieman, G. Büchi, B.H. Walker, J. Amer. Chem. Soc., 79, 5558 (1957).

239. S. Hirano, H. Hara, T. Hiyama, S. Fujita, H. Nozaki, Tet., 31, 2219 (1975).

240. M. Toda, M. Hayashi, Y. Hirata, S. Yamamura, Bull. Chem. Soc. Japan, 45, 264 (1972).

241. G.E. Gream, R. Stafford, unpublished work.

242. J.F. M. Oth, Pure Appl. Chem., 25, 573 (1971).

243. F.A.L. Anet, J. Amer. Chem. Soc., 84, 671 (1962).

244. G. Schröder, J.F.M. Oth, R. Merenyi, Angew. Chem. Int. Ed., 4, 752 (1964).

245. Z. Luz, S. Meiboom, J. Chem. Phys., 59, 1077 (1973).

246. L.A. Paquette, Tet., 31, 2855 (1975).

247. G.I. Fray, R.G. Saxton, "The Chemistry of Cyclooctatetraene and its Derivatives", (Cambridge University Press, Cambridge), 1978.

248. J. Bordner, R.G. Parker, R.H. Stanford, Jr., Acta. Cryst. B., 28, 1069 (1972).

249. O. Bastiansen, L. Hedberg, K. Hedberg, J. Chem. Phys., 27, 1311 (1957).

250. M. Traetteberg, Acta. Chem. Scand., 20, 1724 (1966).

251. F.A.L. Anet, A.J.R. Bourn, Y.S. Lin, J. Amer. Chem. Soc., 86, 3576 (1964).

252. M.J.S. Dewar, A. Harget, E. Haselbach, J. Amer. Chem. Soc., 91, 7521 (1969).

253. G. Wipff, U. Wahlgren, E. Kochanski, J.M. Lehn, Chem. Phys. Letters, 11, 350 (1971).

254. C.J. Finder, D. Chung, N.L. Allinger, Tet. Lett., 4677 (1972).

255. N.L. Allinger, J.T. Sprague, C.J. Finder, Tet., 29, 2519 (1973).

256. R. Huisgen, F. Mietzsch, Angew. Chem. Internat. Ed., 3, 83 (1964).

257. R. Huisgen, F. Mietzsch, G. Boche, H. Seidl, Chem. Soc. Special Publ. no. 19, 3 (1965).

258. R. Huisgen, G. Boche, A. Dahmen, W. Hechtl, Tet. Lett., 5215 (1968).

259. R. Huisgen, W.E. Konz, G.E. Gream, J. Amer. Chem. Soc., 92, 4105 (1970).

260. L.A. Paquette, D.R. James, G.H. Birnberg, J. Amer. Chem. Soc., 96, 7454 (1974).

261. Reference 15a, p. 1084.

262. J.L.v. Rosenberg, J.E. Mahler, R. Pettit, J. Amer. Chem. Soc., 84, 2842 (1962).

263. S. Winstein, H.D. Kaesz, C.G. Kreiter, E.C. Friedrich, J. Amer. Chem. Soc., 87, 3267 (1965).

264. S. Winstein, Chem. Soc. Special Publ. no. 21, 5 (1967).

265. S. Winstein, Quart. Rev., 23, 141 (1969).

266. J.M. Bollinger, G.A. Olah, J. Amer. Chem. Soc., 91, 3380 (1969).

267. L.A. Paquette, Angew. Chem. Internat. Ed., 17, 106 (1978).

268. L.A. Paquette, J.R. Malpass, T.J. Barton, J. Amer. Chem. Soc., 91, 4714 (1969).

269. C.E. Keller, R. Pettit, J. Amer. Chem. Soc., 88, 606 (1966).

270. S. Winstein, C.G. Kreiter, J.I. Brauman, J. Amer. Chem. Soc., 88, 2047 (1966).

271. P. Warner, D.L. Harris, C.H. Bradley, S. Winstein, Tet. Lett., 4013 (1970).

272. C.E. Keller, R. Pettit, J. Amer. Chem. Soc., 88, 604 (1966).

273. M.S. Brookhart, M.A.M. Atwater, Tet. Lett., 4399 (1972).

274. P. Ahlberg, D.L. Harris, M. Roberts, P. Warner, P. Seidl, M. Sakai, D. Cook, A. Diaz, J.P. Dirlam, H. Hamberger, S. Winstein, J. Amer. Chem. Soc., 94, 7063 (1972).

275. L.A. Paquette, M.J. Broadhurst, P. Warner, G.A. Olah, G. Liang, J. Amer. Chem. Soc., 95, 3386 (1973).

276. R. Huisgen, J. Gasteiger, Tet. Lett., 3661 (1972).

277. R. Huisgen, J. Gasteiger, Tet. Lett., 3665 (1972).

278. W.J. Hehre, J. Amer. Chem. Soc., 95, 5807 (1973).

279. R. Huisgen, J. Gasteiger, Angew. Chem. Internat. Ed., 11, 1104 (1972).

280. W.L. Jorgensen, J. Amer. Chem. Soc., 98, 6784 (1976).

281. G.E. Gream, R. Huisgen, unpublished data, referred to in reference 53.

282. M. Tamura, J. Kochi, Synthesis, 303 (1971).

283. M. Mular, Ph.D. Thesis, The University of Adelaide, 1974.

284. R.D. Wagner, B.Sc.(Hons.) Thesis, The University of Adelaide, 1977.

285. A.B. Evnin, R.D. Miller, G.R. Evanega, Tet. Lett., 5863 (1968).

286. R. Huisgen, W.E. Konz, U. Schnegg, Angew. Chem. Int. Edn., 11, 715 (1972).

287. J. Gasteiger, R. Huisgen, Angew. Chem. Int. Edn., 11, 716 (1972).

288. R. Huisgen, J.P. Ortega, Tet. Lett., 3975 (1978).

289. R. Huisgen, Accts. Chem. Res., 10, (a) p. 117 (b) p. 199 (1977).

290. L.H. Simons, J.J. Lagowski, J. Org. Chem., 43, 3247 (1978).

291. A.C. Cope, A.C. Haven, Jr., F.L. Ramp, E.R. Trumbull, J. Amer. Chem. Soc., 74, 4867 (1952).

292. A.E. Gillam, E.S. Stern, "An Introduction to Electronic Absorption Spectroscopy in Organic Chemistry", p. 303-304, (Edward Arnold, London), 1957.

293. F.A.L. Anet, I. Yavari, Tet. Lett., 4221 (1975).

294. J.B. Stothers, "Carbon-13 NMR spectroscopy", p. 333-337, (Academic Press, N.Y. and London), 1972.

295. V. Henri, L. Pickett, J. Chem. Phys., 7, 439 (1939).

296. E. Pesch, S.L. Friess, J. Amer. Chem. Soc., 72, 5756 (1950).

297. W.v.E. Doering, W.R. Roth, Tet., 19, 715 (1963).

298. R. Auman, J. Knecht, Chem. Ber., 109, 174 (1976).

299. A.C. Cope, L.L. Estes, Jr., J. Amer. Chem. Soc., 72, 1128 (1950).

300. C.L. Osborn, T.C. Shields, B.A. Shoulders, J.F. Krause, H.V. Cortez, P.D. Gardner, J. Amer. Chem. Soc., 87, 3158 (1965).

301. v.W.R. Roth, Annalen, 671, 10 (1964).

302. C.N.R. Rao, "Ultra-Violet and Visible Spectroscopy", p. 90, (Butterworths, London), 1961.

303. Reference 294, p. 33.

304. G.C. Levy, G.L. Nelson, "Carbon-13 Nuclear Magnetic Resonance for Organic Chemists", p. 29-32, (Wiley-Interscience), 1972.

305. A.I. Vogel, "A Text-book of Practical Organic Chemistry", third edition, p. 167, (Longmans, London), 1964.

306. L.F. Fieser, M. Fieser, "Reagents for Organic Synthesis", Vol. 1, p. 1198, (Wiley, N.Y.), 1968.

307. R.M. Moriarty, T.D.J. D'Silva, Tet., 21, 547 (1965).

308. H.J. Kötzsch, Chem. Ber., 99, 1143 (1966).

309. H.J. Koetzsch, E. Behr, Germany patent, 1,275,528 (C1.C.07c), 22-Aug. 1968 (Chemical Abstracts, 69, 95933t (1968)).

310. R.E.A. Dear, W.B. Fox, R.J. Fredericks, E.E. Gilbert, D.K. Huggins, Inorg. Chem., 9, 2590 (1970).

311. F.R. Jensen, J.J. Miller, S.J. Cristol, R.S. Beckley, J. Org. Chem., 37, 4341 (1972).

312. A.I. Vogel, "A Textbook of Quantitative Inorganic Analysis", third edition, p. 325, (Longmans, London), 1962.

313. V.M. Micovic, S. Stojcic, M. Bralovic, S. Mladenovic, D. Jeremic, M. Stefanovic, Tet., 25, 985 (1969).

314. R.N. Shreve, J.H. Lux, Ind. Eng. Chem., 35, 306 (1943).

315. Reference 305, p. 275.

316. K. Ahmad, F.M. Strong, J. Amer. Chem. Soc., 70, 1699 (1948).

317. F.L.M. Pattison, J.E. Millington, Can. J. Chem., 34, 757 (1956).

318. W.G. Kofron, L.M. Baclawski, J. Org. Chem., 41, 1879 (1976).

319. Reference 305, p. 974.

320. R.W. Bost, G.F. Deebel, J. Elisha Mitchell Sci. Soc., 66, 157 (1950), (Chemical Abstracts, 46, 6093i (1952)).

321. J.J. Eisch, G.R. Husk, J. Org. Chem., 31, 3419 (1966).

322. H. Christol, M. Mousseron, F. Plenat, Bull. Soc. Chim. Fr., 543 (1959).

323. D.F. Koster, A. Danti, J. Phys. Chem., 69, 486 (1965).

324. L.M. Porter, F.F. Rust, J. Amer. Chem. Soc., 78, 5571 (1956).

325. Reference 305, p. 516.

326. J. Gasteiger, G.E. Gream, R. Huisgen, W.E. Konz, U. Schnegg, Chem. Ber., 104, 2412 (1971).

327. A.C. Cope, D.J. Marshall, J. Amer. Chem. Soc., 75, 3208 (1953).

328. L.A. Paquette, R.E. Wingard, Jr., J.M. Photis, J. Amer. Chem. Soc., 96, 5801 (1974).