A

Thesis

entitled

"Aromatisation of Diacetylenes"

submitted in part fulfilment of the
requirements for admittance to the Degree

of

Doctor of Philosophy

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by

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CONTENTS

SUMMARY

The thesis is divided into three parts.

PART I.

The base-catalysed isomerisation of hepta-1, 6-diyne to toluene has been investigated using a variety of base-solvent systems. The best results were obtained by refluxing the diyne with a 10% solution of potassium *t*-butoxide in diglyme. A number of straight chain diacetylenes have been prepared and aromatised, by this method, to isomeric mixtures of mono- and *o*-disubstituted benzenoid hydrocarbons in which the most symmetrically substituted *o*-isomers predominated. The reaction is general for this type of diacetylene and the aromatic mixtures were obtained in 60-70% yield. The macrocycle, cyclotetradeca-1, 8-diyne, and the dienyne, octadeca-9, 12-dien-6-ynoic acid, also aromatise, but not the tetraene, ethyl arachidonate. A mechanism involving internal Diels-Alder cyclisation of a conjugated allene-diene intermediate is suggested. An empirical method of correlating the structures of isomeric *o*-dialkyl benzenes to their G.L.C. retention times is put forward.

PART II.

1, 2, 5, 6- Tetrabromocyclooctane has been dehydrobrominated with potassium t-butoxide in diglyme to a mixture of isomeric hydrocarbons containing mainly benzocyclobutene, styrene and a compound believed to be bicyclo [4.2.0] octa-1, 3, 6-triene. Cyclooctatetraene and an unknown compound are present in trace quantities only. This constitutes a new two stage synthesis of benzocyclobutene from readily available starting material.

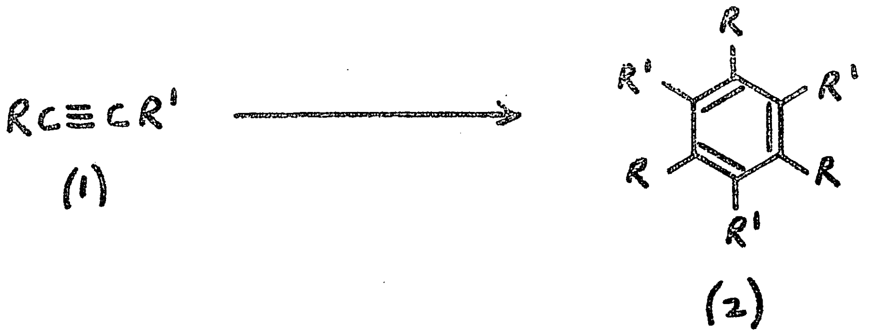
Cyclooctatetraene has also been isomerised under the same basic conditions to the same isomeric mixture as that above. An additional component, thought to be bicyclo [4.2.0] octa-2, 4, 7- triene, is also present. The relative amounts of these components are dependent on the reaction temperature. This is the simplest synthesis of benzocyclobutene yet devised and the yield compares favourably with those obtained by other routes.

PART III.

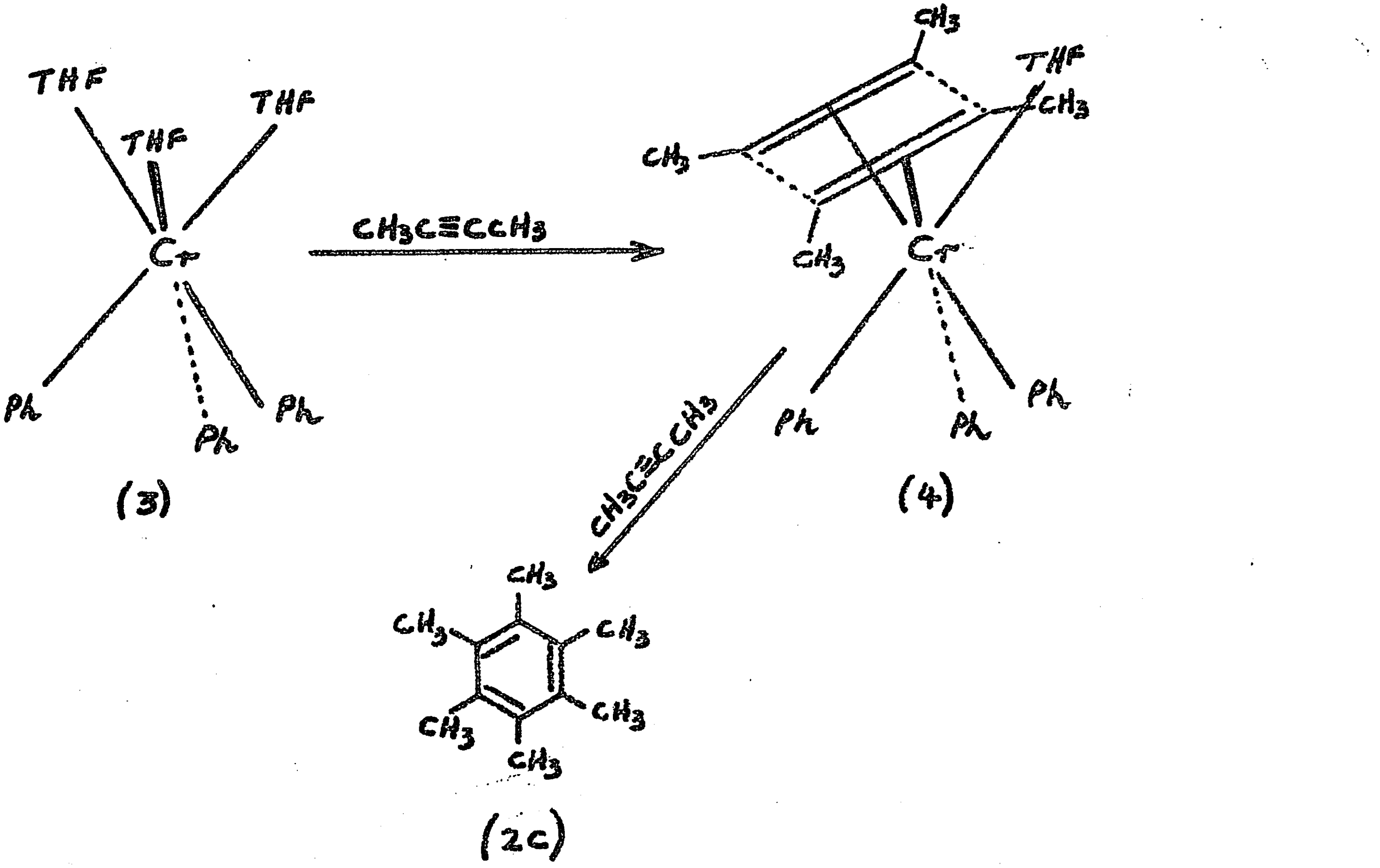
The stereomutation of cis to trans-undec-4-ene during hydrogenation over palladium catalyst has been investigated, and the extent of stereomutation related to the catalyst concentration. The hydrogenation of cis-undeca-1, 7-diene has also been studied.

PART I

THE AROMATISATION OF DIACETYLENES.



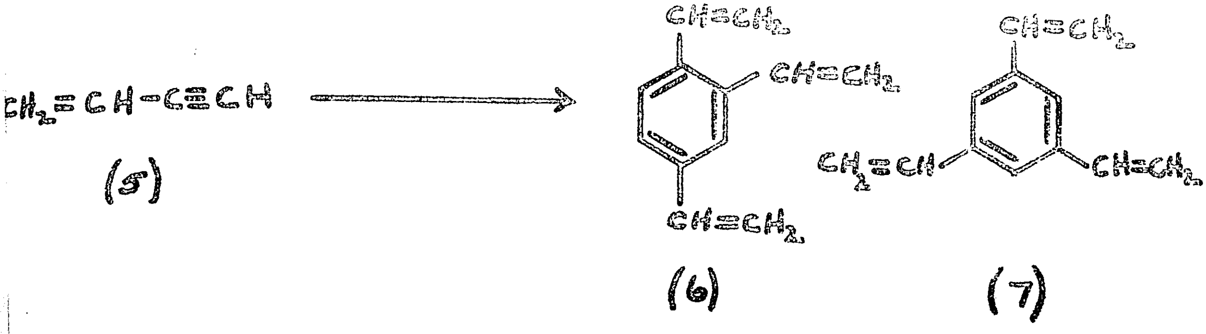
(a) $R = R' = H$
(b) $R = H, R' = CH_3$
(c) $R = R' = CH_3$

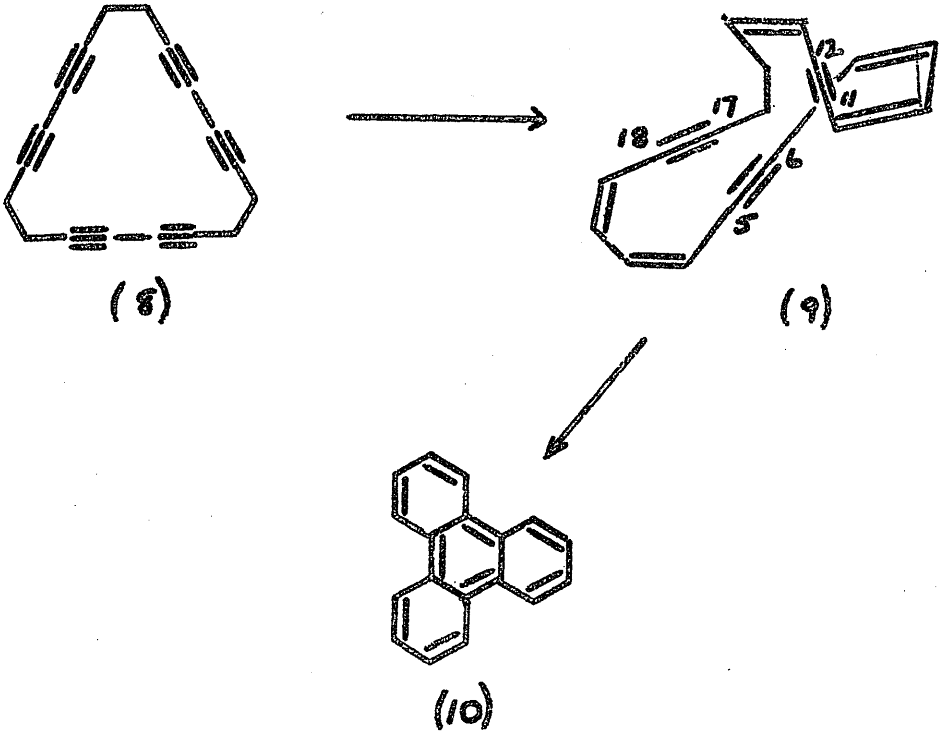


INTRODUCTION

Since its discovery in 1866 by Berthelot,[1] the polymerisation of acetylene (Ia) to benzene (2a) at red heat has remained the first, possibly the most tangible and certainly the most easily remembered reaction of acetylene presented to chemistry students. The reason for this is probably the simplicity of its formal representation which easily encompasses the analogous reactions, discovered by Fittig[2] and Aldedingen,[3] of the higher homologues methyl (1b) and dimethylacetylene (1c) to mesitylene (2b) and hexamethyl benzene (2c), respectively.

These polymerisations remained for many years the only examples of aromatisation of acetylene, or simply substituted acetylenes, until the trend for chemical sophistication led to the discovery of Ziegler type catalysts which could 'condense' the triple bonds to the catalyst surface, there polymerising under very mild conditions.[4] The uses of this elegant technique have been reviewed by Zeiss[5] and the pertinent example of the trimerisation of dimethyl acetylene (1c) to hexamethyl benzene (2c) over a triphenyl chromium catalyst in tetrahydrofuran is explained by stepwise replacement of the tetrahydrofuran ligands in (3) to form the 'tetramethylcyclobutadiene' metal comples (4) which can then undergo an external Diels-Alder addition of


CH₂=CH−C≡CH
(5)
CH=CH₂
CH=CH₂
CH=CH₂
(6)
CH=CH₂
CH₂=CH
CH=CH₂
(7)


(8)
12
11
17
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5
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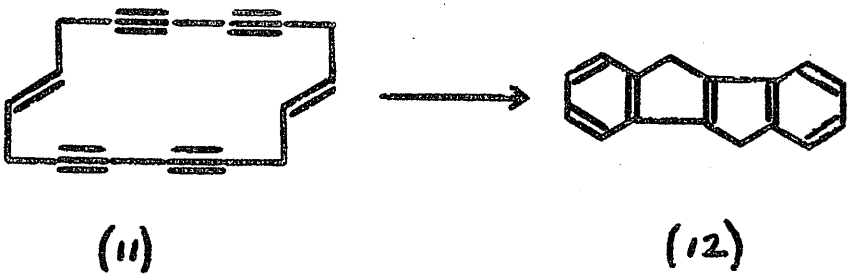
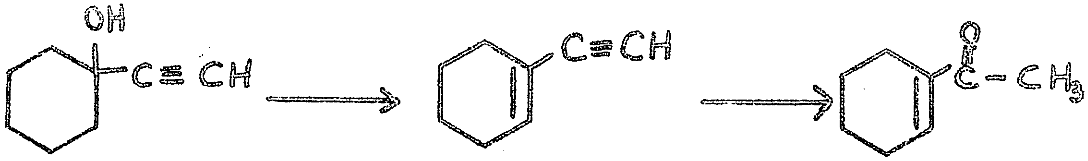

(11)
(12)

dimethylacetylene giving (2c). A particularly good illustration of the chemical potential of this type of catalytic polymerisation is furnished by the trimerisation of vinylacetylene (5) to 1, 2, 4- or 1, 3, 5-trivinyl benzene, (6) and (7), at -10^{0} over triisobutylaluminium/titanium tetrachloride.[6]

Current interest in carcinogenic compounds led Badger and his colleagues[7] to investigate the tars coproduced with benzene in Berthelot's polymerisation of acetylene at red heat. They found, besides benzene, a wide array of aromatic hydrocarbons including toluene, o - xylene, styrene, naphthalene, fluorene, phenanthrene and many polynuclear aromatic hydrocarbons. Compounds of this latter type have been encountered by Sondheimer in his significant research into macrocyclic poly-ynes and poly-enes. Thus the macrocyclic cyclooctadecahexayne (8) and cyclohexadecadientetrayne (11), obtained by oxidative coupling of the corresponding diynes, give triphenylene (10)[8] and 10-diphenylsuccindene (12),[9] respectively, when treated with strong base. In the former case, the reaction is believed to go by base-catalysed isomerisation of (8) to the non-planar 1,3,7,9,13,15-cis-hexaene-5,11,17-triyne (9), a model of which shows that C(6) is close to C(11), C(12) to C(17), and C(8) to C(5). Transannular interaction across these positions is then suggested as a likely pathway to triphenylene (10). A similar argument can



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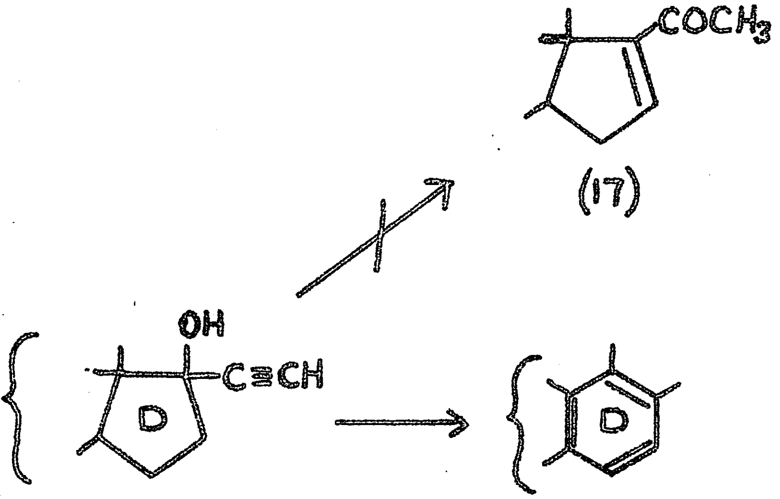
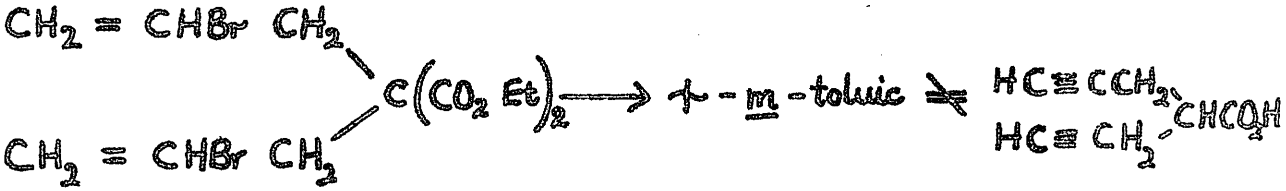


(17)

(16) (18)



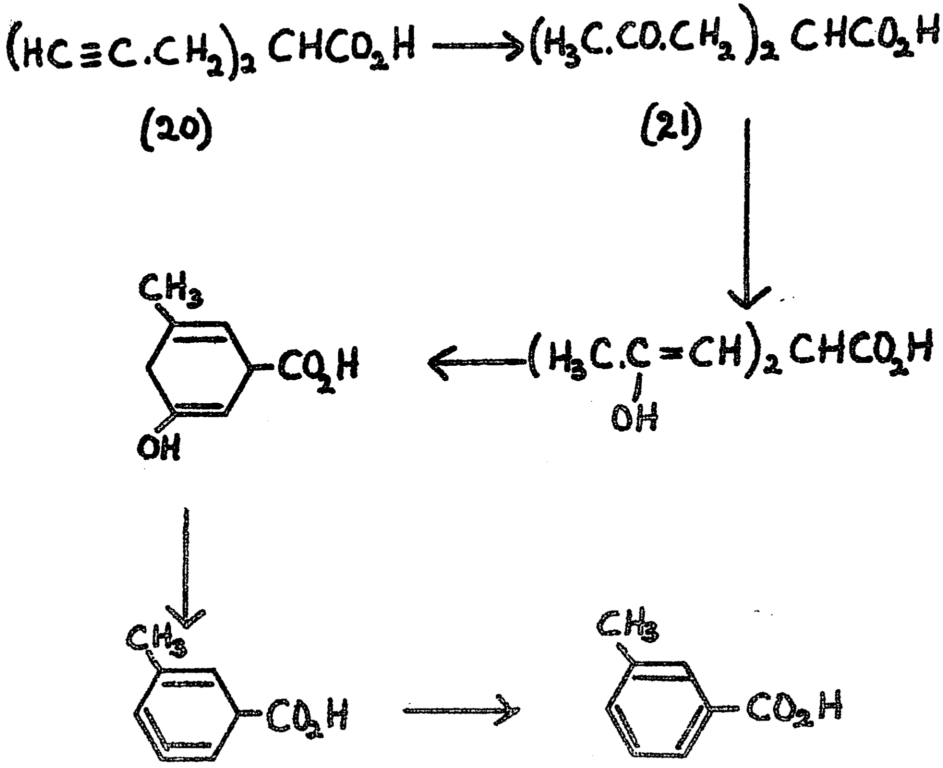
(19) (20)

be applied to the formation of the succindene.

A further isolated example of the aromatisation of acetylenes comes from the unlikely source of steroid chemistry. Much evidence[10, 11] has indicated that the formic acid induced isomerisation of ethynyl carbinols leads almost entirely to the α, β - unsaturated methyl ketones by initial dehydration followed by hydration of the conjugated ethynyl grouping.[12] Thus 1-ethynylcyclohexanol (13) gives initially 1-ethynylcyclohexene (14) which hydrates to the α,β -unsaturated methyl ketone (15). In an attempt to introduce a methyl ketone into ring D of a steroid by this method, Hardegger[13] found that a 17β -hydroxy -17α -ethynylandrostene (16) gave not the required ketone (17), but presumably by dehydration with concurrent methyl migration, ring expansion and aromatisation, an aromatic ring D(18). Jacques[14] found exactly the same rearrangement in the pregnane series, and suggested that the mechanism involves a series of Wagner-Meerwin rearrangements.

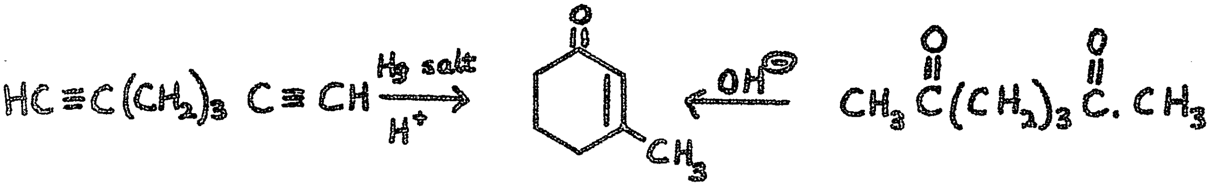
In connection with the hydration of 1-ethynylcyclohexene, Levina[15] discovered in 1938 that this and the related ethynylcyclohexane both gave a high yield of ethyl benzene when heated over a platinum catalyst at 200°.

There remains one other example of the aromatisation of an acetylenic derivative described in the literature, and since it

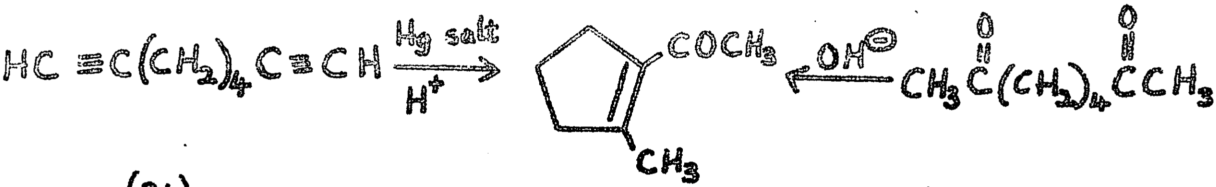


(20) (21)

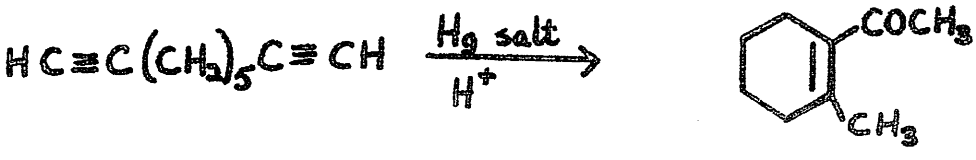
(22)



(23) (24) (25)



(26) (27) (28)



(29) (30)

provides the foundation of the present work, will be dealt with in greater detail. In 1907, Perkin and Simonsen,[16] then investigating approaches to cyclopropane, discovered that condensation of 1,2,3-tribromopropane with diethyl malonate gave besides the expected product, γ-bromoallyl malonate, a small quantity of high boiling ester believed to be γ, γ'-dibromodiallyl malonate (19). Hydrolysis of this ester gave a monocarboxylic acid, ψ-*m*-toluic acid, m.p. 47°, to which the structure of dipropargyl acetic acid (20) was assigned, on the basis that the acid analysed for $C_8H_8O_2$, gave copper and silver salts, and was instantly oxidised by alkaline permangate solution. This acid possessed the unique property of being easily isomerised to m-toluic acid (22); boiling with water or dilute sulphuric for two hours, and hydrobromic acid were effective, but not heat alone. Perkin proposed the unlikely reaction scheme shown involving condensation of the initial hydration product, diacetonyl acetic acid (21).

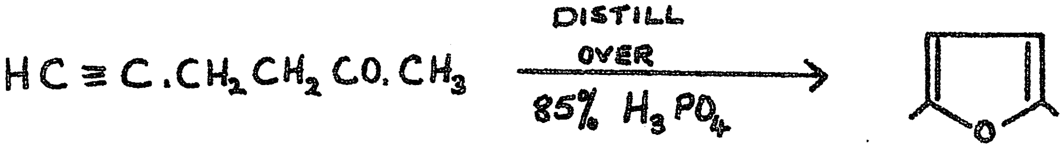
A number of facile hydrations and cyclisations of acetylenic compounds is known . Kon and Everett[17] have reported that attempted purification of hepta-1, 6-diyne (23) via the mercury salt, (mercuric iodide followed by hydrochloric acid and steam distillation), led to high yields of the unsaturated ketone (24). Ketones shown to be (27) and (30) were also obtained from octa-1, 7-diyne (26)

$$HC\equiv C.CH_2Br + CH_2(CO_2Et)_2$$

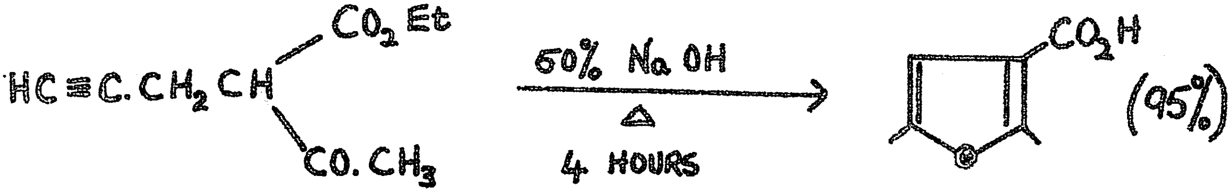
$$\downarrow$$

$$(HC\equiv C.CH_2)_2CHCO_2H + (HC\equiv C.CH_2)_2C(CO_2H)_2$$

(20) (31)



(32)



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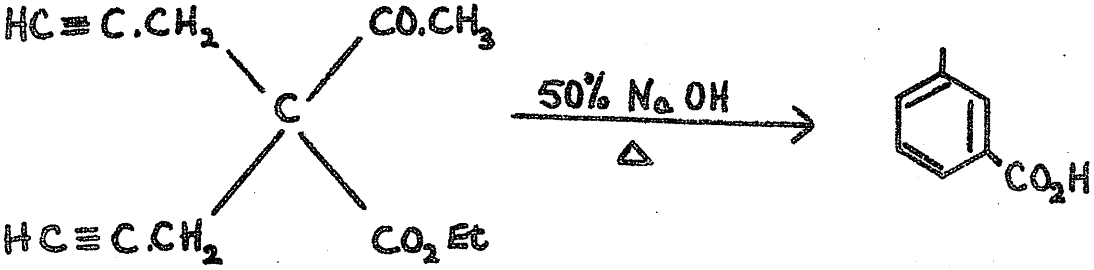


(34)

and nona-1, 8-diyne (29), respectively. Compounds (24) and (27) had previously been obtained by the action of 40% alkali on hepta-2, 6-dione (25) and octa-2, 7-dione (28), respectively.

The conversion of ψ -m-toluic acid into m - toluic acid, however, remains a singular reaction. Recently two groups of French workers have described the preparation of dipropargyl acetic acid (20) and its derivatives, and a number of closely related acids, ketones and esters.

Gaudemar[18] obtained (20) from a condensation between acetoacetic ester and 1-bromoprop-2-yne. A similar condensation with malonic ester gave a 50% overall yield of (20), and in addition, dipropargyl malonic acid (31). Decarboxylation was found to occur easily with this acid, but the products were not identified.

Colonge and Gelin[19] have described the reactions of (32) and (33) shown on the opposite page. Rearrangement involving an allenic intermediate is postulated for the latter reaction and for the formation of m-toluic acid from the ester (34).

Dipropargyl acetic acid (20), m.p. 45.5°, obtained in high yield by Eglinton (unpublished) by the route shown from the condensation of propargyl bromide and diethyl malonate, was recovered unchanged from treatment with boiling water, boiling 10% sulphuric acid or hydrobromic in acetic. Similarly, refluxing with methanolic potassium hydroxide had no effect. Thus, despite

$$HC\equiv C.CH_2Br \quad + \quad CH_2(CO_2Et)_2$$

$$\Big\downarrow \; OEt^{\ominus}$$

$$(CH\equiv C.CH_2)_2 \; C(CO_2Et)_2 \qquad (82\%)$$

$$\Big\downarrow \; \begin{array}{l} KOH/aq.\ MeOH \\ \text{2 HOURS}/100^{\circ} \end{array}$$

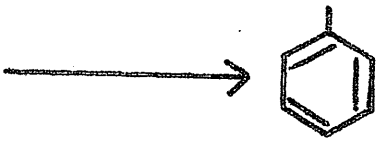
$$(CH\equiv C.CH_2)_2 \; C(CO_2H)_2 \qquad (84\%)$$

$$\Big\downarrow \; \begin{array}{l} \text{boiling pyridine} \\ \text{90 min.} \end{array}$$

$$(CH\equiv CCH_2)_2 \; CHCO_2H \qquad (95\%)$$

(20)

$HC\equiv C(CH_2)_3C\equiv CH$



(23)

the similarity in melting point, it seemed unlikely that ψ-m-toluic acid was in fact dipropargyl acetic acid.

The problem remained intriguing, and Eglinton and Harkin[20] in 1955 tried to repeat Perkin's original route. The experimental details given by Perkin for the crucial step, the hydrolysis of the dibromo diester (19) are, however, particularly vague, and nothing approaching ψ-m-toluic acid was isolated. They did, however, discover that dipropargyl acetic acid (20) could be easily isomerised in high yield to m-toluic acid by simply refluxing the acid with potassium hydroxide in ethylene glycol or water. Continuing along these lines, Eglinton and Rosenfeld[21] obtained spectroscopic evidence which supported that the simple hydrocarbon precursor, hepta-1, 6-diyne, was isomerised to toluene with 10% potassium hydroxide in ethylene glycol for four hours at 120°, and it was at this point that the work described in the proceeding pages was begun.

$$CH_3\,CH_2\,C\equiv CH \xrightarrow{\qquad} CH_3\,C\equiv C\,CH_3$$

(35) (36)

$$CH_2Br.\ CHBr\,(CH_2)_8\,CO_2H$$

(37)

$$\Big\downarrow{\scriptstyle OH^{\ominus}}$$

$$HC\equiv C(CH_2)_8\,CO_2H \quad + \quad CH_3\,C\equiv C\,(CH_2)_7\,CO_2H$$

(38) (39)

$$CH_3\,(CH_2CH{=}CH)_3\quad CH_2\,(CH_2)_6\,CO_2H$$

(40)

$$\Big\downarrow$$

$$CH_3\,(CH_2)_2\,CH{=}CH{-}CH{=}CH{-}CH{=}CH\,(CH_2)_8\,CO_2H$$

(41)

DISCUSSION

The facile isomerisation of both dipropargyl acetic acid and hepta-1, 6-diyne with strong base, immediately suggested that some type of base-catalysed prototropic rearrangement was operating. The first object of this work was the establishment of the best conditions for this reaction, which in turn demanded a knowledge of the basic systems previously used in anionotropic rearrangements.

Base-catalysed isomerisation of acetylenes.

The isomerisation of acetylenic hydrocarbons under alkaline conditions, a much easier process than that for the corresponding olefins, was discovered by Favorskii[22] in 1888. He found that treatment of but-1-yne (35) with potassium ethoxide in ethanol gave a high yield of but-2-yne (36). It was therefore not surprising when Krafft,[23] several years later, found that some undec-9-ynoic acid (39) was produced in a preparation of undec-10-ynoic acid (38) involving elimination of hydrogen bromide from 10, 11-dibromoundecanoic acid (37) with alcoholic hydroxide at 180°.

When it was realised that the production of conjugation was an important factor in the troublesome formation of colour in fatty acids and oils, the food industry sponsored investigations into the processes involved, paying particular attention to the alkaline saponification step so widely used in the industrial production of many essential acids and oils. These investigations showed that alkaline hydroxide solutions in alcohol or water were effective at high temperature[24] (e.g. ca. 225° in the latter case), while solutions in glycol facilitated conjugation at lower temperatures. Thus linolenic acid (40) readily forms 10, 12, 14 - octadecatrienoic acid (41) in a boiling solution of 25% potassium hydroxide in glycol.[25]

Alkali metal catalysis of olefinic isomerisation, generally slow below 100°, is extremely effective if the metal is dispersed on alumina.[26] A very active catalyst is produced in this way, and isomerisations occur at much reduced temperatures, for example, but-1-ene is isomerised to an equilibrium mixture of cis- and trans-but-2-ene over sodium on alumina at -60°,[27] while pentene gives the analogous reaction at 30°.[28] Unconjugated dienes are rapidly conjugated, and cyclic dienes are not only isomerised, but dehydrogenated forming aromatic systems at room temperature. The surface area does not account for the catalyst activity, and the suggestion is[27] that the actual catalyst is formed by reaction of the olefin with the sodium on the alumina surface; apparently a combination of support, ionic and metallic sodium is necessary. Surprisingly this method has never been

$$HO_2C.CH_2C\equiv C\cdot C\equiv CCH_2CO_2H$$

(42)

$$\downarrow$$

$$HO_2CCH=CH-CH=CH-C\equiv CCO_2H$$

(43)

$$HO_2CCH_2CH_2C\equiv C-C\equiv CCH_2CH_2CO_2H$$

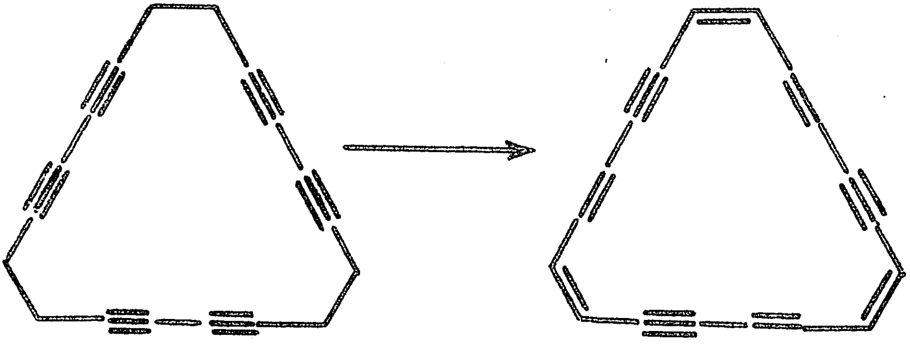
(44)

$$\downarrow$$

$$HO_2C(CH=CH)_4CO_2H$$

(45)

$$\underset{(46)}{HC\equiv CCH_2CO_2H} \rightarrow \underset{(47)}{CH_2=C=CHCO_2H} \rightleftharpoons \underset{(48)}{CH_3C\equiv CCO_2H}$$



(49) (50)

used for acetylenes.

Closer to the present problem is the recent work by Jones and Whiting on prototropic rearrangements of diacetylenic dicarboxylic acids from which conjugated dien-yne and tetraene dicarboxylic acids are obtained. Thus hexa-2, 4-diyne-1, 6-dicarboxylic acid (42) and octa-3,5-diyne-1,8-dicarboxylic acid (44) give respectively hexa-1,3-dien-5-yne-1,6-dicarboxylic acid (43) and octa-1,3,5,7-tetraene-1,8-dicarboxylic acid (45),[29] when treated with 10% aqueous potassium hydroxide at 55°. Similarly, but-3-ynoic acid (46) gives both the allene (47), and but-2-ynoic acid (48) with 18% aqueous potassium carbonate at 40-90°.[30] These rearrangements are in complete agreement with the findings of Jacobs[31] in the pentyne system (see later).

In the acetylenic hydrocarbon series, Sondheimer[32] has successfully isomerised the cyclooctadecahexayne (49), prepared by oxidative coupling of hepta-1,6-diyne, to the fully conjugated hexaenetriyne (50) using potassium t-butoxide in t-butanol at 90°. This is the nearest approach to an isomerisation of hepta-1, 6-diyne itself.

In conclusion, neglecting alkali metal catalysis, any base varying in strength between potassium hydroxide and t-butoxide in any hydroxylic solvent has provided a system suitable for the isomerisation of olefins and acetylenes. It is interesting to note,

Table 1.

Initial base/solvent system investigations determined by refluxing hepta-1, 6-diyne with a 10% solution of the base. The table shows the approximate heights of the significant peaks present in the infrared spectra of the products.

Run number	$H-C \equiv C$ *ca.*3300 cm.$^{-1}$	$C=C=C$ 1950	$C=C-C=C$ 1640	Vinyl ether 1200-1000	Toluene 730
1	*s*	*m*	*s*	*s*	
2	-	-	-	*m* - *s*	*m*
3	*s*	-	*w*	-	-
4	*w*	-	*m* - *s*	*m*	*s*
5	*m*	*m*	*m*	-	*m* - *s*
6	-	-	*w*	-	*m* - *s*

Run 1. Sodium hydroxide/glycol for 8 hours.

Run 2. Sodium hydroxide/methyl cellosolve for 8 hours.

Run 3. Sodium hydroxide/dimethyl formamide for 8 hours.

Run 4. Potassium *t*-butoxide/*t*-butanol for 3 hours.

Run 5. Sodamide/diglyme for 2 hours.

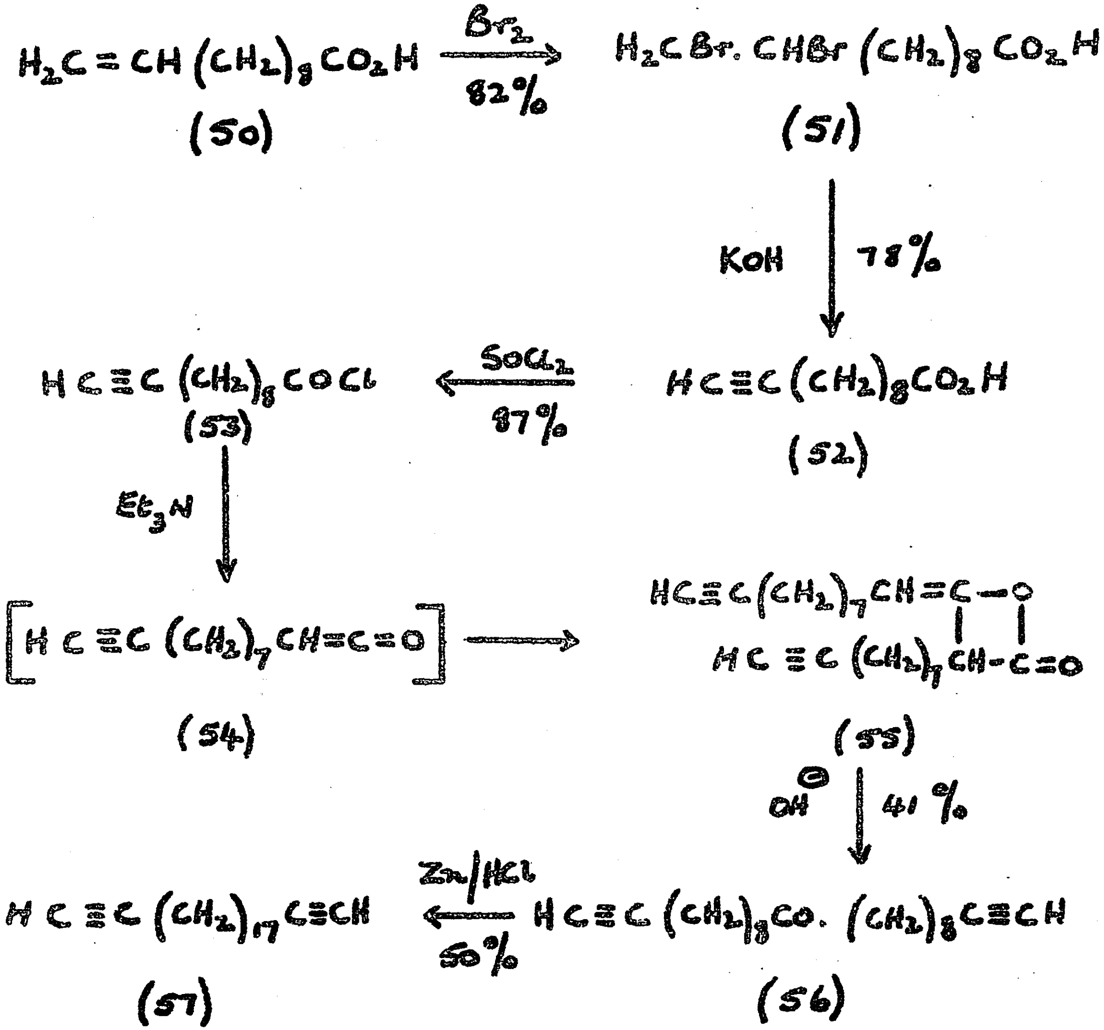
Run 6. Potassium *t*-butoxide/diglyme for 15 minutes.

at this point, that although the rate of prototropic rearrangement brought about by potassium t-butoxide in methanol is less than in t-butanol, this latter system has the disadvantage of forming a t-butoxide/t-butanol complex which is insoluble below 80°. Hydrogen bonding between the solvent and the catalyst is also believed to inhibit catalytic action.[33]

Catalyst efficiency.

The effectiveness of various base-solvent systems in promoting the prototropic rearrangement of hepta-1,6-diyne to toluene was investigated by refluxing the hydrocarbon with the basic system for suitable times. The extent of reaction was determined by a superficial examination of the significant peaks at 3300 (H-C≡C), 1950 (allene), 1650-1630 (double bonds), 1200-1000 (vinyl ether) and 727 cm.$^{-1}$ (γ-CH in toluene). The results obtained are tabulated in table 1.

Systems employing solvents containing a free hydroxyl group were ineffective, as was dimethylformamide. Both sodamide, previously known to catalyse deuterium exchange in hydrocarbons,[34] and potassium t-butoxide in diglyme (diethylene glycol dimethyl ether) were effective. Reaction with the former system was slower, and strong allenic and ethylenic absorption was present in the infrared spectrum of the product. The significance of this absorption will be discussed later.


H₂C=CH(CH₂)₈CO₂H
(50)
Br₂
82%
H₂CBr.CHBr(CH₂)₈CO₂H
(51)
KOH
78%
HC≡C(CH₂)₈CO₂H
(52)
SOCl₂
87%
HC≡C(CH₂)₈COCl
(53)
Et₃N
HC≡C(CH₂)₇CH=C=O
(54)
HC≡C(CH₂)₇CH=C—O
HC≡C(CH₂)₇CH-C=O
(55)
OH⊖
41%
HC≡C(CH₂)₈CO.(CH₂)₈C≡CH
(56)
Zn/HCl
50%
HC≡C(CH₂)₁₇C≡CH
(57)

Potassium t-butoxide in diglyme proved completely satisfactory, and was used in all subsequent isomerisations. As previously mentioned, there are disadvantages in the use of t-butoxide in the presence of t-butanol, and even traces of the alcohol treatly retard prototropic exchange. Sublimed butoxide would therefore have been ideal. The reactions did however proceed smoothly if the last traces of the alcohol were removed at 160° under oil pump pressure until the butoxide started to sublime.

Suitable aromatisation conditions having been established, the next step was to investigate the generality of the reaction. To this end, a series of diacetylenic hydrocarbons were prepared and subjected to this basic treatment.

Preparation of diacetylenic hydrocarbons.

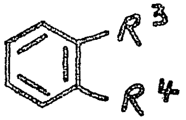
There is an excellent review by Marzak[35] on the general methods of preparation of acetylenes. Most of the diacetylenes listed in table 2 were prepared by well established routes which are fully described in the experimental. The physical constants and yields of the diacetylenes so formed were compatible with those quoted by previous authors. Heneicosa-1,20-diyne (57) was prepared by the route shown.

Isomerisations of diacetylenic hydrocarbons.

The aforementioned diynes were isomerised by refluxing them with a 10% solution of potassium t-butoxide in diglyme for

TABLE 2.

AROMATISATION OF DIACETYLENIC HYDROCARBONS WITH 10% POTASSIUM *t*-BUTOXIDE IN DIGLYME AT REFLUX (161°).

$R^1C\equiv C(CH_2)_nC\equiv CR^2 \longrightarrow$ 

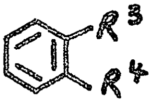
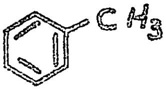
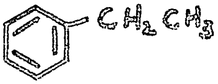
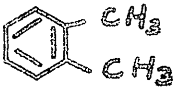
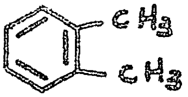
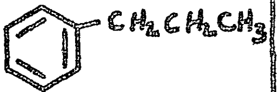
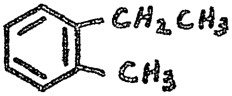
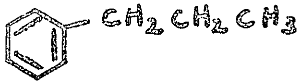
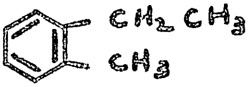
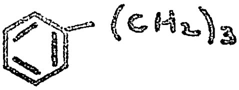
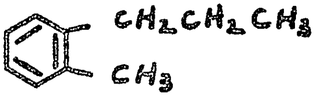
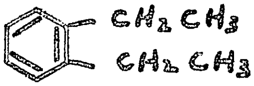
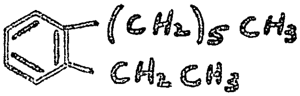
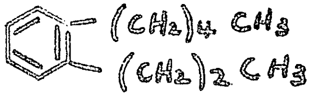
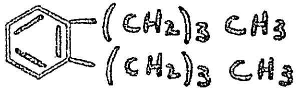
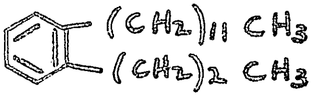
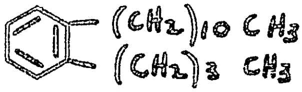
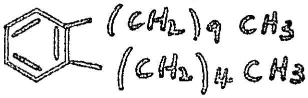
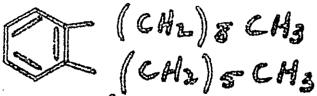
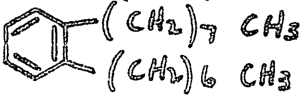
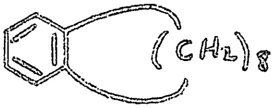
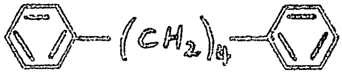
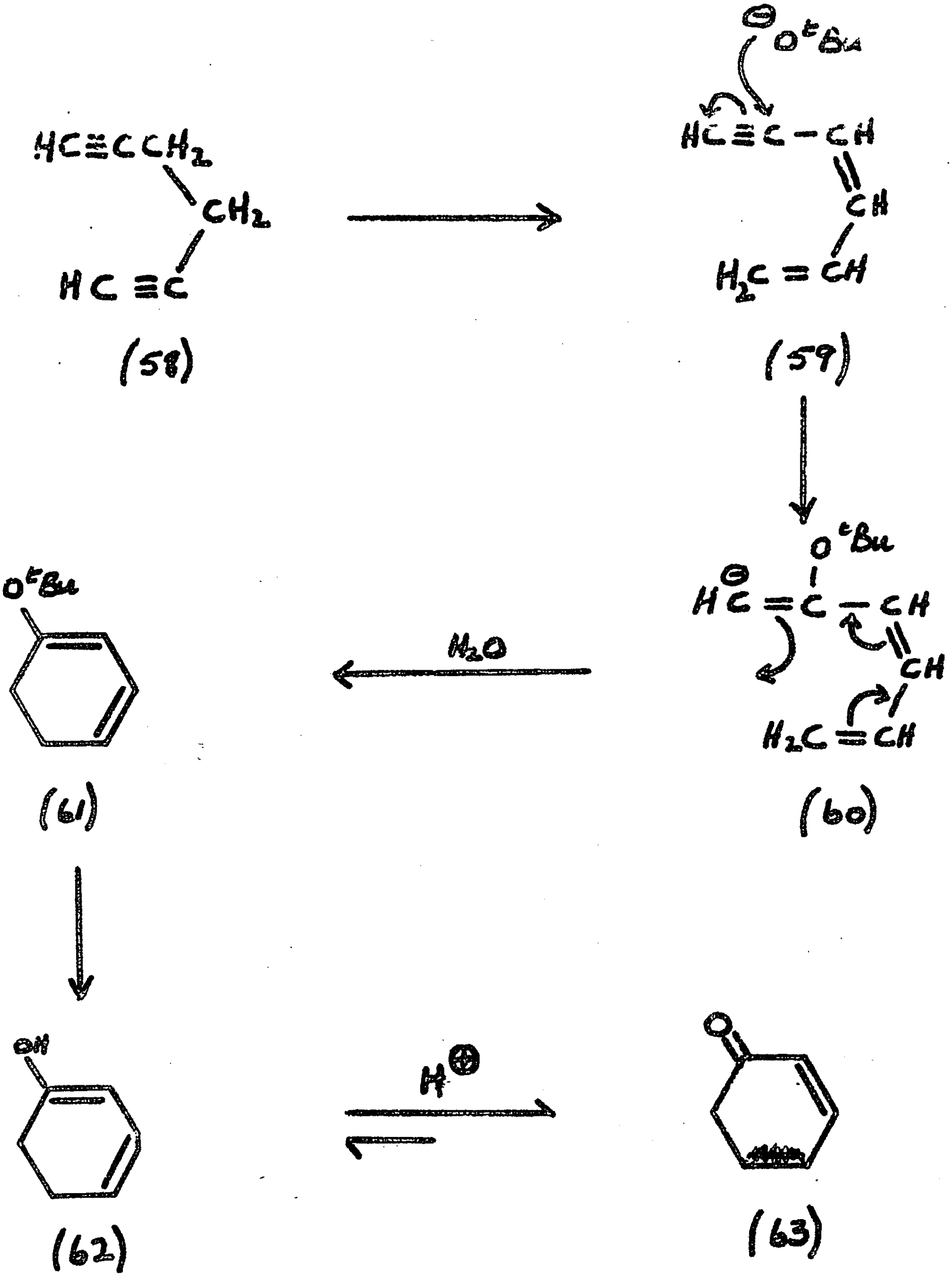
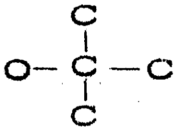
RUN NUMBER	R^1	R^2	n	REFLUX TIME (hrs)	PRODUCT COMPOSITION	% OF COMPONENTS IN PRODUCT	YIELD OF 
1	H	H	2	7	VINYL ETHER	?	—
2	H	H	3	4		100	35
3	H	H	4	8	 	22 61	72
4	Et	Et	0	15	  ?	28 64 8	68
5	H	H	5	6	  ?	17 77 6	69

TABLE 2 CONTINUED

6	Me	Me	3	7	 	15 85	70
7	H	H	6	12	  	5 } >90	66
8	H	H	10	18	   3 UNKNOWNS	8 23 52 17	62
9	H	H	17	24	     UNKNOWNS	1 4 4 9 55 27	64
10	$-(CH_2)_5-$		5	16	 UNKNOWN STARTING DIYNE	70 20 8	62
11			0	15		?	42



HC≡CCH2
CH2
HC≡C
(58)
O^tBu
HC≡C–CH
CH
H2C=CH
(59)
O^tBu
HC=C–CH
CH
H2C=CH
(60)
H2O
O^tBu
(61)
OH
(62)
H⊕
O
(63)

Infrared spectra of:	Frequency (cm.$^{-1}$):	Assignment
(a) Product from attempted isomerisation of hexa-1, 5-diyne (58)	3010	H - C = C
	1630, 1570	C = C-C = C
	1360	$C - CH_3$.
	1200 - 1050	ether
	890	 $O-\overset{C}{\underset{C}{C}}-C$
	952	**trans** C=C
(b) Acid hydrolysis product from (a)	3350	intermolecular bonded - OH ?
	1710	
	1680	br., conjugated
	1640	dien-one
	1590	

periods generally determined by infrared analysis of aliquots removed at reasonable intervals. The term 'solution' is perhaps misleading in this text because although most of the butoxide dissolved, some always remained as a milky suspension. The results of these isomerisations are summarised in table 2 and expanded below.

Hexa-1,5-diyne (table 2, run 1)

The infrared spectra of aliquots removed after reaction times of one, three and seven hours were substantially the same, and suggested that a conjugated dienyl-t-butyl ether was produced. If initial prototropic rearrangement of the diyne (58) gave the conjugated dien-yne (59), then butoxide addition could conceivably occur, as shown, giving an intermediate of the type (60). Ring closure and hydrolysis of this would then give the cyclohexadienyl-t-butyl ether (61); a structure which completely agrees with the spectral data shown. Acid hydrolysis of this should give the ketone (63).

Acid hydrolysis of the reaction product gave an oil and the significant absorption bands, with their tentative assignments in the infrared of this oil are shown opposite. The general broadening of peaks in this spectrum suggest the presence of an enol, possibly as the tautomeric system (62)-(63). The oil gave a deep red, unstable D.N.P. derivative which rapidly darkened on attempted recrystallisation and gave an insoluble solid which could not be characterised.

Since it was obvious that benzene had not been formed, investigations into the product from hexa-1,5-diyne were discontinued.

Hepta-1,6-diyne (table 2, run 2).

Treatment of this diyne with basic systems other than t-butoxide have already been discussed. With this system, strong γ-CH aromatic absorption occurred in the infrared of the product after only fifteen minutes at 130°, which reflects the efficiency of these conditions for promoting prototropic rearrangements. In an isomerisation at reflux for four hours, the yield of toluene by infrared analysis was 35%, and the hydrocarbon was identified by infrared and oxidation to benzoic acid. The reaction proceeds only slowly below 100°. Thus, when heated on a steam bath for five hours, weak allenic and ethylenic absorption appeared although there was no noticeable change in ethynyl absorption.

Octa-1,7-diyne (table 2, run 3)

The infrared spectra of aliquots removed after reaction times of one and eight hours contained no ethynyl absorption, and were identical in the 700-800 cm.$^{-1}$ region to the superimposed spectra of ethyl benzene and o-xylene. Alkaline permanganate oxidation of the product gave a mixture of benzoic and phthalic

Table 3.

Analytical G.L.C. of the Isomerisation Product of Octa -3, 5 - diyne.

Run number	Diglyme		Ethyl benzene		unknown		o-xylene	
	R_T*	%+	R_T	%	R_T	%	R_T	%
1	9.8	-	-	-	-	-	-	-
2	-	-	11.4	-	-	-	-	-
3	-	-	-	-	-	-	16.7	-
4	-	-	11.8	28	14.2	8	17.4	64

Chromatograms run on 5% Apiezon 'L' with an Argon flow rate of 50 ml./min.

Run

1. Diglyme at 47°
2. Ethyl benzene at 50°
3. o-Xylene at 50°.
4. Isomerisation product of octa-3, 5-diyne at 48°.

* R_T is the apparent retention time in min.

\+ Relative amount of component in the product determined by area measurement and expressed as a percentage.

acids. The yield in this oxidation coupled with the yield of o-xylene by quantitative infrared analysis, using the band at 746 cm.$^{-1}$, showed that the product contained 22 and 61% of ethyl benzene and O-xylene, respectively. The yield of these isomers from the diyne was 72%.

Octa-3,5-diyne (table 2, run 4)

The infrared spectrum of the product after a reaction time of fifteen hours was identical to that obtained from octa-1,7-diyne above. The boiling point and refractive index of the product were comparable to those of o-xylene, and was oxidised to a mixture of benzoic and phthalic acids.

The analytical G.L.C. of the product (table 3) indicated a three component system. Two of these, present as 28 and 64% of the product, were identified by mixed chromatograms as ethyl benzene and o-xylene, respectively. The third component, present as 8% of the mixture, was not diglyme, and remains unknown.

The yield and product distribution from the isomerisations of these C_8 diynes was almost the same, which possibly means that the same intermediate, prior to cyclisation, has been produced by prototropic rearrangement in both cases.

Table 4.

Analytical G.L.C. of the Isomerisation Product of Nona - 1, 8 - diyne.

Run number	n - propyl benzene		unknown		o-ethyl toluene	
	R_T	%	R_T	%	R_T	%
1	9.6	-	-	-	-	-
2	9.9	6	12.3	17	13.1	77

These chromatograms were run on 5% Apiezon 'L' at 70°, Argon flow rate 50 ml./min.

Run 1. n - Propyl benzene

Run 2. Isomerisation product of nona - 1, 8 - diyne.

Nona-1,8-diyne (table 2, run 5)

The infrared spectra of the products obtained, after reaction times of one and six hours, were identical to the superimposed spectra of n-propyl benzene and o-ethyl toluene, and all the peaks could be accounted for on this basis. Oxidation gave phthalic and a trace of benzoic acid.

Analytical G.L.C. of the product (table 4) again showed three components present as 6, 17, and 77% of the mixture. The first of these was identified by a mixed chromatogram as n-propyl benzene, while the last is presumably o-ethyl toluene. The yield of these isomers from the diyne was 69%. The structure of the third component is unknown.

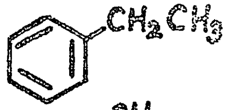
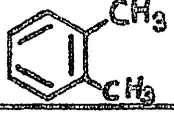
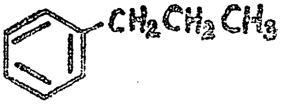
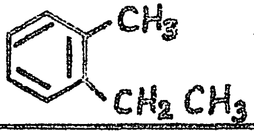
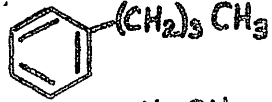
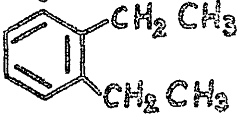
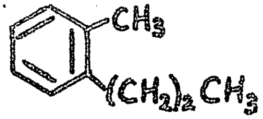
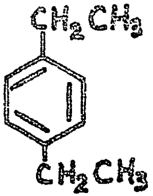
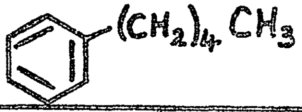
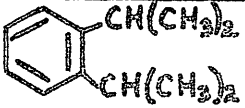
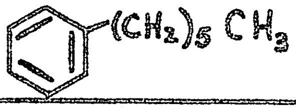
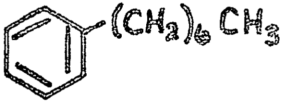
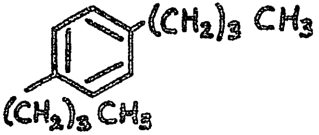
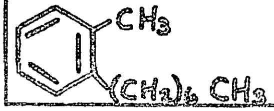
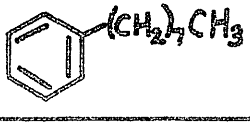
Nona-2,7-diyne (table 2, run 6)

The infrared spectrum of an aliquot removed after one hour at reflux was identical to that of the product from the 1,8-isomer above. Similarly, after seven hours, oxidation gave the same products. G.L.C.s were not run, and the yield of aromatic product was estimated, only approximately, as 70% from the oxidation results.

The isomerisation of these C_9 diynes clearly shows that as the chain length of the diyne increases, the proportion of o-disubstituted product also increases. The overall yields are not effected.

TABLE 5.

BOILING-POINTS OF AROMATIC HYDROCARBONS

COMPOUND	NUMBER OF CARBONS	BOILING-POINT °C.
	8	136
		144·4
	9	159·2
		165·1
	10	183·3
		183·4
		184·8
		183·7
	11	205·4
	12	209
		226
	13	245·5
	14	224
		263
		264·5

Deca-1,9-diyne (table 2, run 7)

The product obtained after twelve hours exhibited only typical aromatic infrared absorption, particularly complex in the aromatic γ-CH region. An interesting situation has now arisen in connection with the difference in boiling points between mono- and *o*-disubstituted aromatic hydrocarbons which are listed in table 5. In C_8 hydrocarbons this difference is *ca.* 8°, the monosubstituted isomer being the lower boiling, in C_9 *ca.* 6°, and in C_{10} there is almost no difference. As this series is continued, there is actually an inversion in boiling point position. Thus *n*-hexyl benzene boils 17° above *o*-diisopropyl benzene, and *n*-octyl benzene 40° above *o*-dibutyl benzene, with *n*-heptyl toluene intermediatory and just below *n*-octyl benzene. Boiling points of isomers containing more than fourteen carbons could not be found in the literature, but taking the trends in this last known range a little further, it would appear that boiling points decrease as the symmetry of *o*-disubstitution increases. Retention of aromatic hydrocarbons on the non-polar stationary phase, Apiezon 'L', will be mainly a function of boiling point, and these trends should be reflected there.

In the present case the boiling points of the expected aromatic products lie at the 'cross-roads', and differences in the retention times of the isomers are expected to be small, if any.

Table 6.

Analytical G.L.C. of the isomerisation of deca-1, 9-diyne.

Run number	n - butyl benzene		o-n-propyl toluene and/or o-diethyl benzene	
	R_T	%	R_T	%
1	11.9	-	-	-
2	12.0	ca. 5	12.6	ca. 95

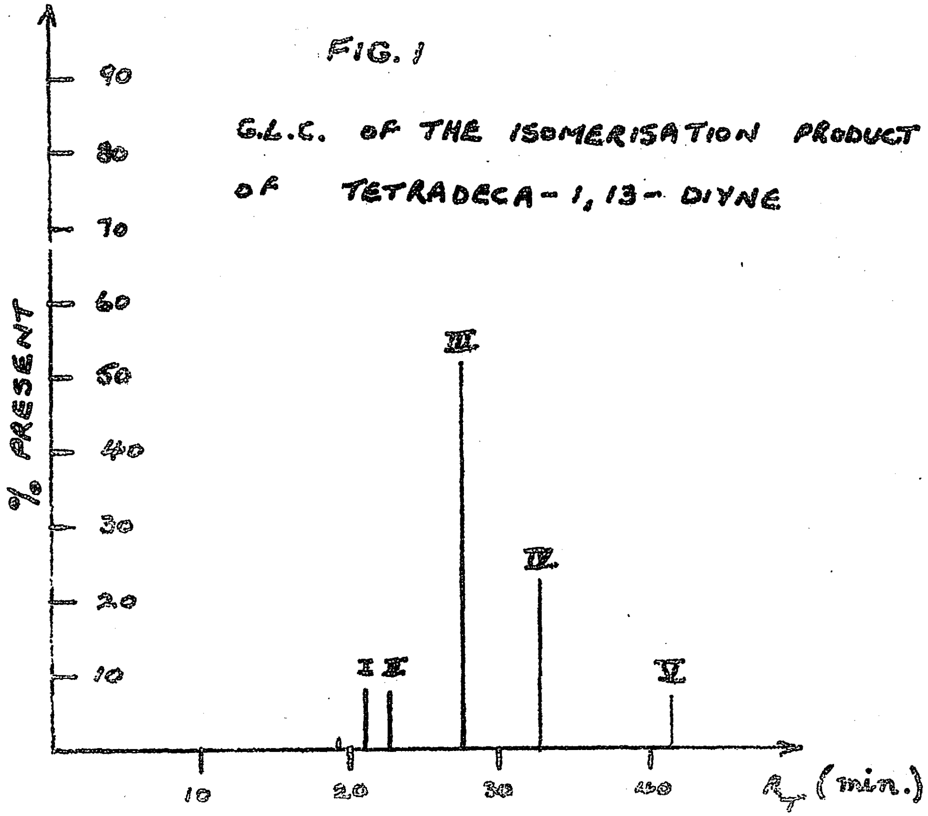
These chromatograms were run on 5% Apl. at 86°, with an Argon flow rate of 50 ml./min.

Run 1. n - Butyl benzene.

Run 2. Isomerisation product of deca-1, 9-diyne.

FIG. 1

G.L.C. OF THE ISOMERISATION PRODUCT OF TETRADECA-1,13-DIYNE

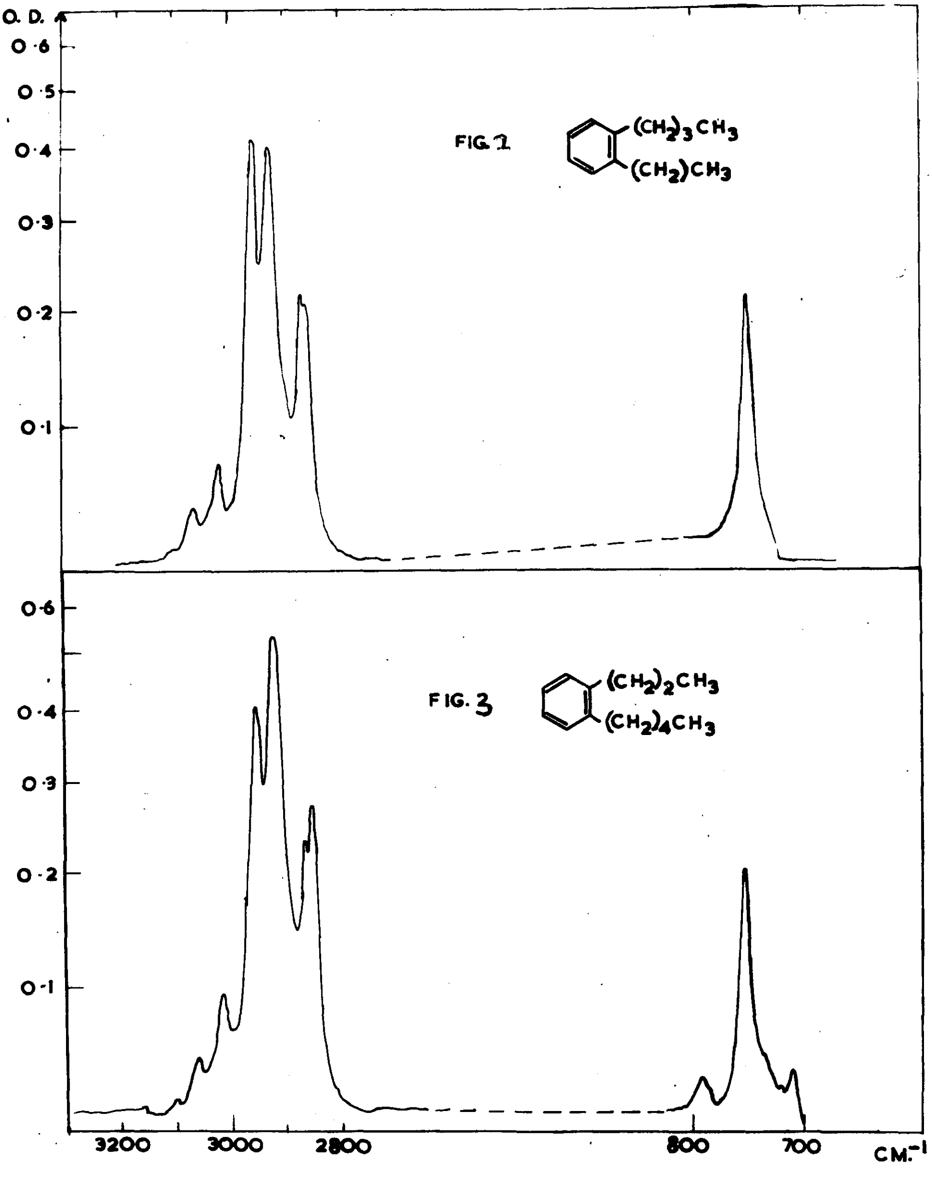


The G.L.C. of the product (table 6) showed only one peak with a shoulder, ca. 5% of the whole, at lower retention time. The retention time of n-butyl benzene and this shoulder were the same, but a mixed chromatogram gave only a general broadening of the main peak with no defined separation. The main peak, by analogy to the previous isomerisations, is probably a mixture of o-n-propyl toluene and o-diethyl benzene in which the latter predominates. The actual product distribution could not be determined by infrared or oxidation, and remains unknown. The yield of aromatic isomers was 66%.

Tetradeca-1,13-diyne (table 2, run 8)

Although ethynyl absorption had completely disappeared from the infrared spectrum of the product after a reaction time of four hours, there was significant allenic and olefinic but only weak aromatic γ-CH absorption. After eight hours, the aromatic γ-CH had strengthened, and after eighteen, the spectrum was typical of a mixture of o-disubstituted benzenoid hydrocarbons.

The G.L.C. of the product, reproduced as a histogram (fig. 1), revealed a six component system in which two, peaks III and IV, predominated as 52 and 23% of the mixture. Because of the boiling point reversals above, it was impossible to assign structures to these on G.L.C. evidence alone, nor was it feasible



INFRARED SPECTRA OF THE ISOMERISATION PRODUCTS OF 1,13-TETRADECADIYNE

FIG.2 G.L.C. PEAK III

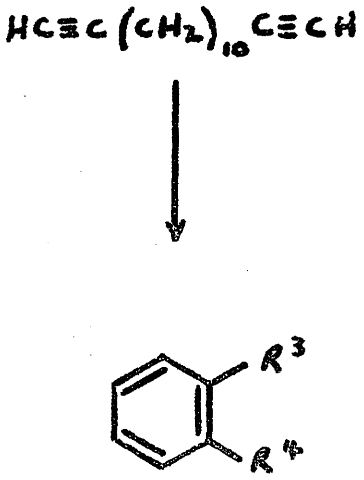
FIG.3 G.L.C. PEAK IV

to prepare all five possible aromatic isomers for comparisons. The peaks on the G.L.C. were, however, sufficiently separated to make preparative G.L.C. practicable, and these main peaks were subsequently separated on the Pye-Argon apparatus using a 10% Apiezon 'L' column. From the preponderance of the most symmetrical isomers in previous isomerisations, structures (64) and (65) were the first choices for the main components.

Infrared analysis of the main products from tetradeca-1, 13-diyne.

The samples from the G.L.C. were trapped in U tubes using acetone/dricold, and despite drying precautions, the collected fractions were inevitably wet. This was apparently caused by condensation just before and just after sample collection when the drying tubes were absent from the U tubes. The concentration of the carbon disulphide solutions used in the infrared analyses were therefore unfortunately unknown; the solutions being dried and diluted until suitable spectra were obtained. The infrared spectra of the components corresponding to peaks III and IV (fig. 1) in the 3000 and 750 cm.$^{-1}$ regions are shown in figures 2 and 3 respectively. Although there is little difference in the γ-CH bands, there are marked intensity differences in the 3000 cm.$^{-1}$ region.

Pokrooskij[52] has examined the C-H vibrational bands of a number of n-alkanes and found that:



(64) $R^3 = R^4 = 4$

(65) $R^3 = 3, R^4 = 5$

(66) $R^3 = 2, R^4 = 6$

where R^3 and R^4 are the number of carbons in the <u>n</u>- alkyl side chains

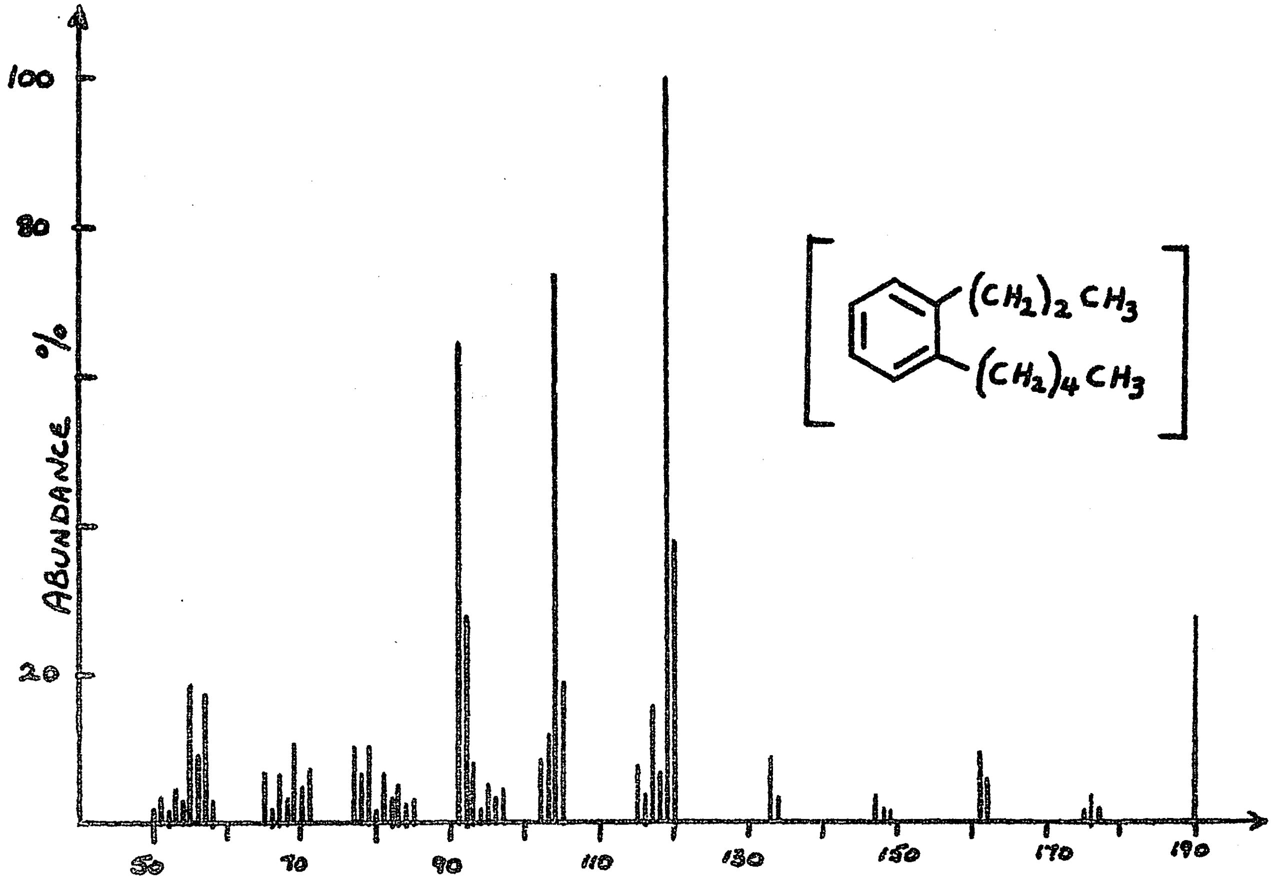
(a) the band at 2924 $cm.^{-1}$ is the C–H vibration of the CH_2 groups and its intensity increases with increasing chain length.
(b) the band at 2957 $cm.^{-1}$ is the C–H vibration of the CH_3 group and its intensity decreases with increasing chain length.

From these considerations the ratio of the intensities of the bands at 2925 and 2957 $cm.^{-1}$ in a structure (65) would be expected to be greater than the same ratio for a structure (64). On these grounds, structure (64) can be assigned to the infrared spectrum (fig. 2) of G.L.C. fraction III, and structure (65) to that of G.L.C. fraction IV (fig. 3). Since the actual intensities of these bands in this series are unknown, these spectra could as easily be assigned to structures (65) and (66) respectively. The actual lengths of the side chains in either one of these components must therefore be known before any definite conclusions can be made from the infrared data.

Mass spectroscopic analysis of the main products from tetradece -1, 13-diyne.

Beynon[53] in his recent book has reviewed correlations between mass spectra and the structures of a number of alkyl benzenes. The predominant dissociation processes in these tend to be those which require the lowest energy, and these processes are mostly those in which a stable ring structure is preserved in

FIG. 5



MASS NUMBER

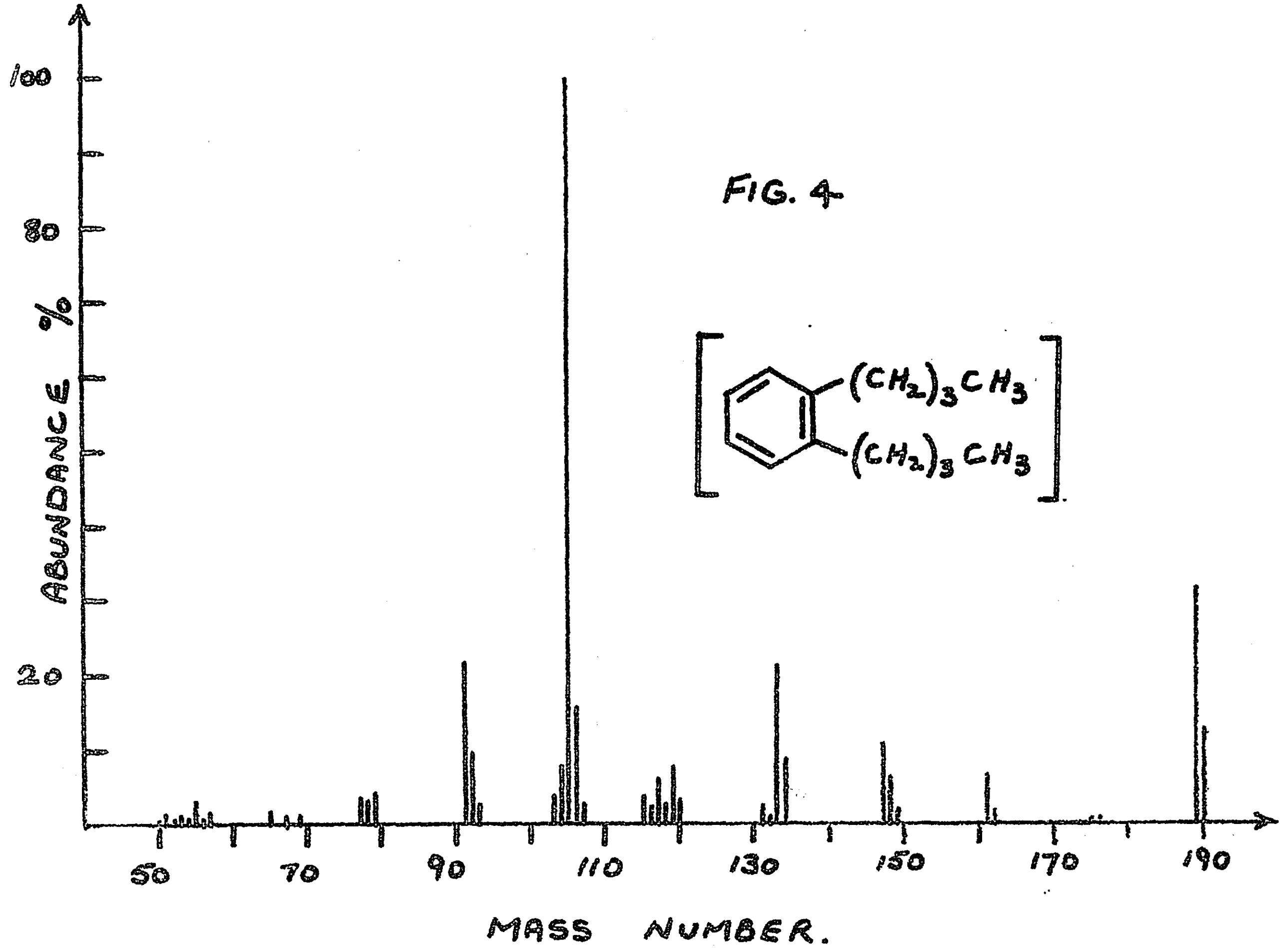
MASS SPECTRUM OF G.L.C. FRACTION IV FROM THE ISOMERISATION OF TETRADECA-1,13-DIYNE.

the ionised fragments. Since the presence of the ring in the alkyl benzenes causes marked differences in bond strengths along the alkyl side chain, the spectra show prominent peaks due to fragmentation at the weakest bond. Thus in alkyl benzenes the strongest ion in the spectra is one of mass 91 corresponding to rupture β - to the ring giving the stable $C_7 H_7^+$ ion.

In poly-alkyl benzenes dissociation - to the ring tends to centre in the side chain which has the longest subsituents on the α- carbon atom, and although mass 91 may remain a prominent peak, it will no longer be the strongest in the spectra. The unsymmetrical structure (65), containing C_3 and C_5 side chains, from the above considerations, would be expected to give a prominent peak corresponding to the loss of $C_5 H_{11}$ by rupture α - to the ring at this side chain. Predictions about the mode of fragmentation of the symmetrical structure (64) are uncertain as there is equal probability of α - and β - rupture.

The mass spectra of G.L.C. fractions III and IV are shown as histograms (figs. 4 and 5). Both have parent peaks of mass 190 ($C_{14} H_{22}$) and lesser peaks of mass 91.

The spectrum of fraction IV (fig. 5) is dominated by a peak of mass 119 corresponding to the loss of a fragment of mass 71, i.e. $C_5 H_{11}$. The next main peak of mass 105 corresponds to further loss of CH_2 giving a stable rearrangement ion which



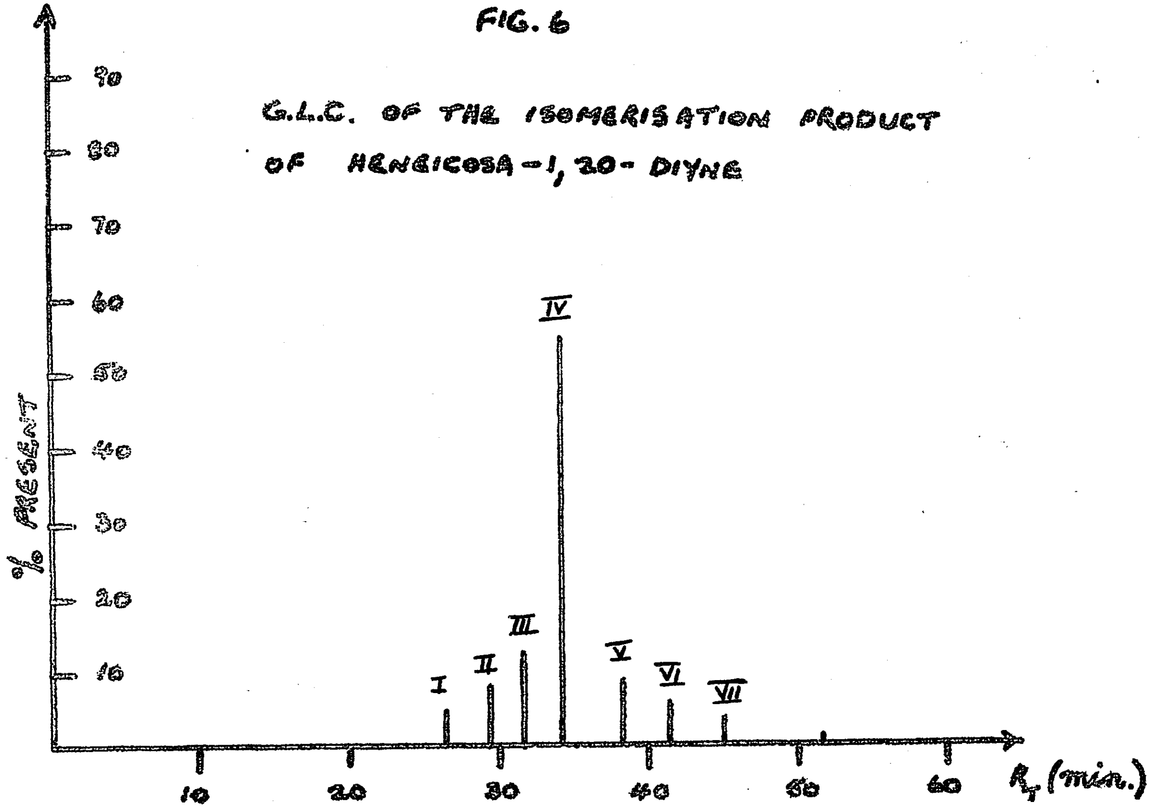
MASS SPECTRUM OF G.L.C. FRACTION III FROM THE ISOMERISATION OF TETRADECA-1,13-DIYNE.

in turn loses CH_2 giving the stable $C_7H_7^+$ ion typical of aromatic structures. From the considerations discussed above, this cracking pattern clearly indicates that fraction IV is o-n-propyl-n-pentyl benzene (65).

The spectrum of fraction III (fig. 4) is completely dominated by a peak of mass 105 presumably caused by β- fragmentation giving this as a stable rearrangement product. There are also a series of peaks corresponding to successive loss of CH_3 and CH_2s from the parent ion, the strongest of these, of mass 133, corresponding to loss of mass 57, i.e. C_4H_9 indicating α- fragmentation at a C_4 side chain. The overall simplicity of this spectrum surely reflects the symmetry of the molecule, and structure (64) is assigned to fraction III, in complete agreement with the arguments based on infrared.

The product from the isomerisation of tetradece -1, 13-diyne has now been shown to be a mixture containing mainly O-dibutyl benzene and o-n-propyl-n-pentyl benzene in 52 and 22% respectively. The other component V of longer retention time is probably o-ethyl-n-hexyl benzene from boiling point considerations. The yield of aromatic isomers from the diyne is 62%, and the structures of the remaining two components I and II are unknown.

FIG. 6



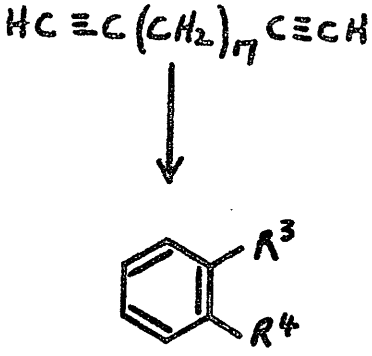
G.L.C. OF THE ISOMERISATION PRODUCT OF HENEICOSA-1,20-DIYNE

Heneicosa -1, 20-diyne (table 2, run 9).

The infrared spectrum of the product after a reaction time of twenty-four hours contained, other than aromatic absorption, bands at 1640, 980 and 710 cm.$^{-1}$ assigned to cis and trans double-bond unsaturation. Hydrogenation resulted in the uptake of one molar equivalent of hydrogen, corresponding to a yield of 75% of aromatic products if the by-products were non-cyclic and completely reduced. Non-aromatic unsaturation had disappeared from the spectrum of the product, but there were now new bands at 2670 w and 810 cm.$^{-1}$ possibly caused by a cycloalkane system.

The discovery that this peak at 710 cm.$^{-1}$ was caused by double-bond absorption was somewhat disconcerting as peaks around this frequency had previously been noted, generally as shoulders, in all the isomerisations of diynes containing more than seven carbons which gave rise to unidentified unknowns. This band had been assigned to aromatic γ- CH and not to double bond absorption, and consequently hydrogenation had not been attempted. The implications of this discovery will be dealt with when the mechanism is discussed.

The G.L.C. of the hydrogenated product, reproduced as a histogram (fig. 6, opp. page), contained eight peaks dominated again by one, peak IV. Attempts to separate this peak by preparative scale G.L.C. were unsuccessful as there was



(67) $R^3 = 7$, $R^4 = 8$

(68) $R^3 = 6$, $R^4 = 9$

(69) $R^3 = 5$, $R^4 = 10$

(70) $R^3 = 4$, $R^4 = 11$

(71) $R^3 = 3$, $R^4 = 12$.

considerable bleeding of the stationary phase, Apiezon 'L'. By analogy to the isomerisation of tetradeca -1, 13-diyne, this main peak was assigned to the most symmetrical o-disubstituted benzenoid isomer n-heptyl-octyl benzene (67), and peaks V - VIII to isomers (68) - (71) respectively. Components (67 - (71) occurred as 73% of the product and the yield of these isomers from the diyne was 64%.

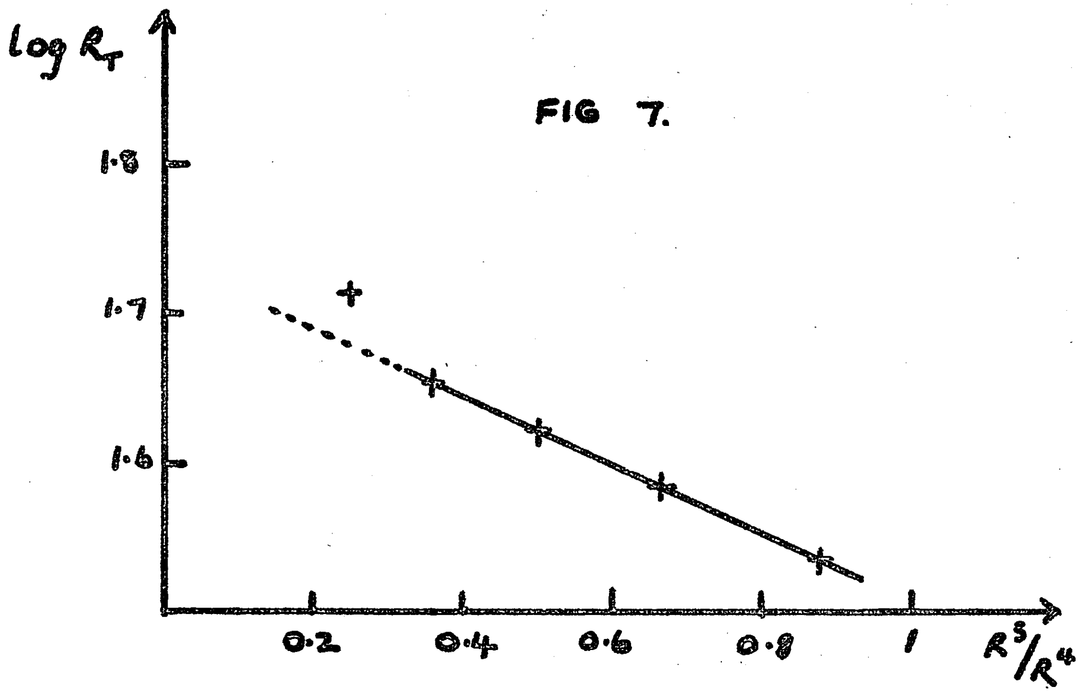
Analogies are never really satisfactory, and some empirical relationship between the retention times of these isomers was sought. Several empirical methods have been used for correlating gas - chromatographic data for solutes in homologous series, and for solutes of similar structure with other physical data. Thus straight lines are usually obtained for plots of the log of the retention time on a given stationaryhp ase against

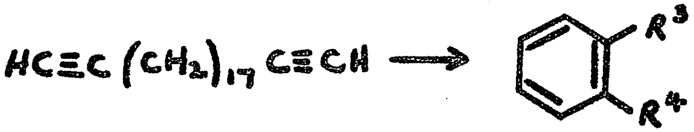
(a) the number of carbon atoms in the molecule [54]

(b) the boiling point of pure solute. [55]

In the present case, the boiling points of compounds (67) - (71) are unknown, and a plot of type (b) could not be made. The following qualitative considerations did, however, lead to a very interesting result. As the structures of these isomers is changed from (67) - (71), polarisation effects within the molecules would remain the same until the length of an alkyl side chain became less than four at which point the dipole moment of the molecule would

FIG 7.





change. This phenomenon, which would effect intermolecular binding and therefore boiling point, is well known in the case of n-alkyl halides.[56] If the alkyl chains are four or more carbon atoms long polarisation effects can therefore be eliminated from boiling point considerations. Changes in boiling point might now be possibly accounted for by changes in molecular packing which might again be directly effected by the ratio of alkyl substituents R^3 and R^4.

It has been found that the plot of the 'substituent ratio' (R^3/R_4) against the log of the retention time of peaks IV - VII, assuming they have the structures (67) - (70), is a straight line (fig. 7). It has further been found that peak VIII, assigned to structure (71), which has a n-propyl side chain and would be expected to have a different dipole moment from the others, deviates from this plot towards a longer retention value, i.e. a higher boiling point.

Unfortunately, other long chain diacetylenes were not prepared and aromatised, and this empirical method could therefore not be tested further. It does, however, add some weight to the validities of the analogies drawn above. The explanations offered for this plot may be extremely crude, but it should be borne in mind that plots (a) and (b) and others like them were used and relied upon for many years before they received theoretical backing quite recently.

Table 7.

G.L.C. of the isomerisation of cyclotetradeca-1, 8-diyne and related compounds.

Run	Diglyme		Hydrogenation products						'X'		'Y'		'Z'			
number	R_T	%	R_T	%	R_T	%	R_T	%	R_T	%	R_T	%	R_T	%	R_T	%
1	.025*	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.1	10.0
3	-	-	-	-	-	-	-	-	.73	2.1	.85	20	1.0	69.4	1.1	8.3
4	-	-	-	-	-	-	-	-	.74	1.0	.85	14.7	1.0	56.6	1.1	27.7
5	-	-	.60	.93	.67	3.3	.72	8	-	-	.83	21.2	1.0	66.2	-	-

Chromatograms run on 5% Apl. at 163-5°,
Argon flow rate 31 ml./min.

Run 1. Diglyme.

2. Cyclotetradeca-1, 8-diyne.

3. Isomerisation product of cyclotetradeca-1, 8-diyne.

4. Isomerisation product of cyclotetradeca-1, 8-diyne plus cyclooctatetra-1, 8-diyne.

5. Hydrogenated isomerisation product of cyclotetradeca-1, 8-diyne.

* Extrapolated.

Cyclotetradece -1, 8-diyne (table 2, run 10)

The product after a reaction time of sixteen hours was an oil with a typically aromatic infrared spectrum containing complex aromatic γ - CH absorption, and bands at 1630 and 698 cm.$^{-1}$ assigned to *cis* double bonds.

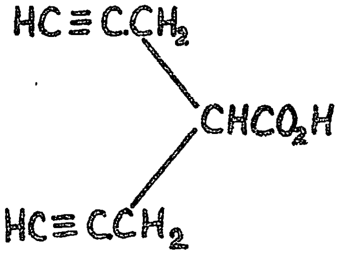
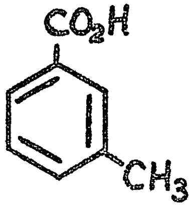
Analytical G.L.C. (table 7) showed the presence of four components, two of which, Y and Z, were present as 70 and 20% of the product. The only other significant component was identified by a mixed chromatogram (table 7, runs 2, 4) as starting material, and was hydrogenated quantitatively presumably to cyclotetradecane. The fourth component X, present as 2% of the mixture, hydrogenated to two new unknowns and was probably a tricyclic isomer of the starting diyne. The hydrogenated mixture could not be separated by alumina chromatography. By analogy to the other isomerisations, product Z was probably benzocyclodecene and was obtained in 62% yield from the diyne. The structure of Y is unknown.

Bis-ethynylcyclohex-1-ene (table 2, run 11)

Bearing in mind the easy isomerisation of ethynylcyclohex-1-ene to ethyl benzene,[15] it was not surprising that the dimer, after a reaction time of fifteen hours gave a 42% yield of 1, 4- diphenylbutane, identified by direct comparison with an authentic sample.

TABLE 8

ISOMERISATION OF MISCELLANEOUS ACETYLENES WITH 10% POTASSIUM $\underline{t}$ - BUTOXIDE IN DIGLYME AT REFLUX (161°).

RUN NUMBER	COMPOUND	REFLUX TIME (HOURS)	PRODUCT	YIELD OF AROMATIC PRODUCT %
1.	 $HC\equiv C.CH_2$ $CHCO_2H$ $HC\equiv CCH_2$	5.		70
2.	$CH_3(CH_2)_4\ (CH{=}CH.CH_2)_4$ $(CH_2)_2.\ CO_2\ Et$	18	CONJUGATED TETRAENE	—
3.	$CH_3(CH_2)_4(CH{=}CH.CH_2)_2$ $C\equiv C(CH_2)_4\ CO_2H$	8	AROMATIC ISOMERS	84

$CH_3(CH_2)_4(CH{=}CHCH_2)_4(CH_2)_2CO_2Et$

(72)

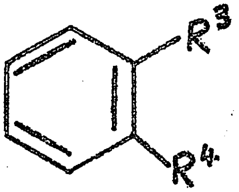
$$\downarrow$$

$R^5(CH{=}CH)_4R^6$

$CH_3(CH_2)_4(CH{=}CHCH_2)_2C\equiv C(CH_2)_4CO_2H$

(73)

$$\downarrow$$



(74) $R^3 = (CH_2)_4CH_3$; $R^4 = (CH_2)_6CO_2H$

(75) $R^3 = (CH_2)_6CH_3$; $R^4 = (CH_2)_4CO_2H$

The isomerisation of miscellaneous acetylenes.

The following acetylenes were isomerised as described for the hydrocarbons, and the results obtained are summarised in table 8.

Dipropargyl acetic acid (table 8, run 1)

After a reaction time of five hours, *m*-toluic acid was isolated in 70% yield and identified by infrared and mixed melting point.

Ethyl arachidonate (72) (table 8, run 2)

No aromatic product was isolated from this skipped fatty acid ester, but the infrared spectrum of the product, after a reaction time of twenty hours, contained considerable absorption between 1650 - 1550 cm.$^{-1}$, indicating that the well-established base-catalysed isomerisation of skipped double bonds into conjugation had occurred. There was some hydrolysis during the reaction and both ester and acid isolated contained these conjugated double-bond bands. As expected, the products were unstable and decomposed on standing at room temperature overnight.

This reaction is important because it shows that four double bonds and presumably four conjugated double-bonds do not aromatise under conditions satisfactory for diynes.

Octadeca -9, 12-dien-6-ynoic acid (73), (table 8, run 3)

The product isolated, after a reaction time of eight hours, was an acid, or mixture of acids, in 84% yield, containing strong aromatic infrared absorption. Alkaline permanganate oxidation of the product gave phthalic acid. The product was probably a mixture of acids (74) - (75), and no attempt was made to separate these. Thus a compound containing a dien-yne system has aromatised, and this must be accounted for in the mechanism.

Summary of results and discussion of mechanism

Any suggested mechanism must account for the following experimental observations:-

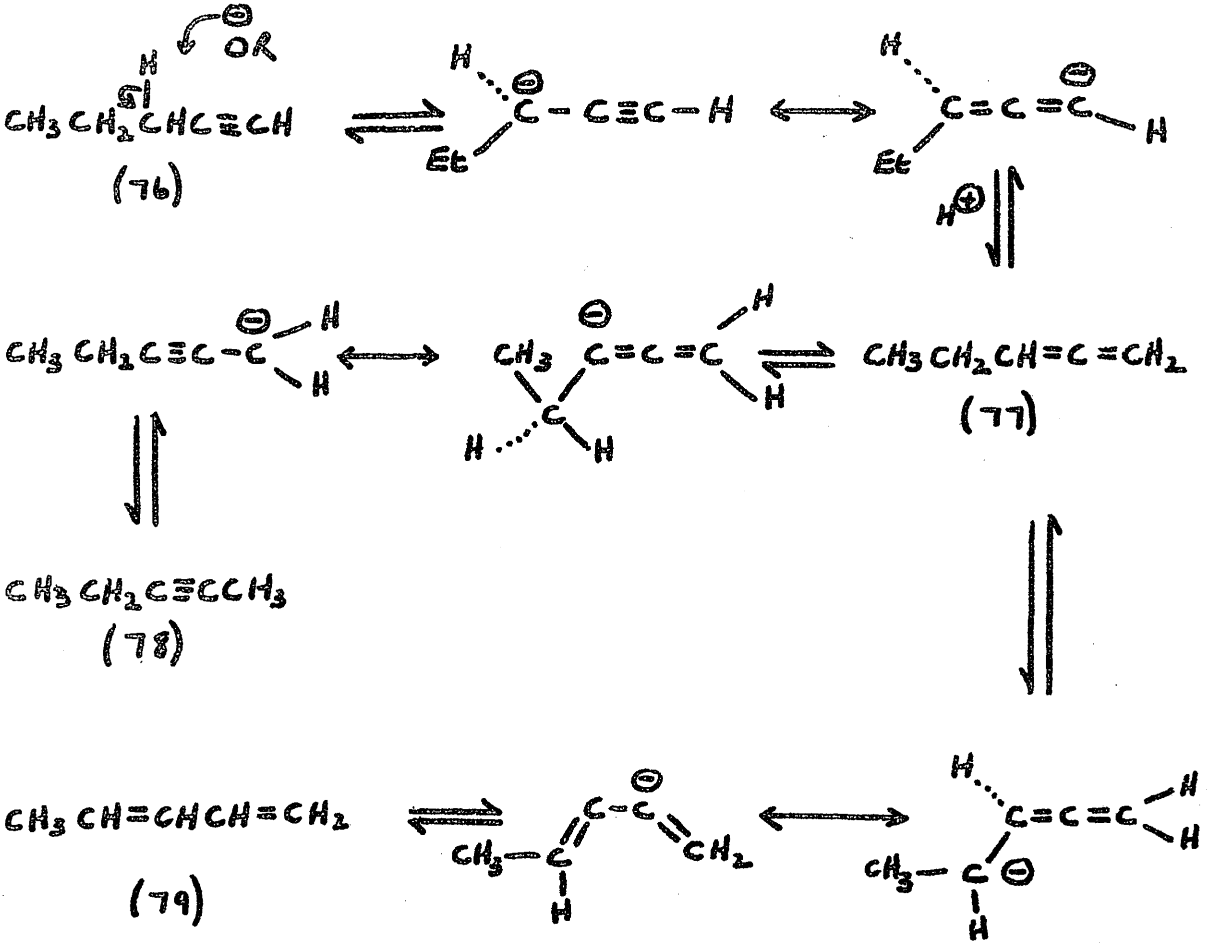
(i) Aromatisation occurs in straight chain diacetylenes which contain seven or more carbon atoms but not, as in the case of hexa-1, 5-diyne, when there are only six. This suggests an essential intermediate containing seven carbons.

(ii) In every case examined introduction of a diacetylene to the basic system produced a change from colourless to yellow which slowly darkened through orange and red to brown at a rate which was approximately proportional to the distance between the triple bonds. This suggests the formation of a conjugated ionic chromophore.

(iii) In isomerisation using potassium t-butoxide in diglyme no intermediate could be detected. However, if the weaker base sodamide was used, the reaction was much slower and the I.R. of samples removed in the early stages of the reaction contained strong allenic and ethylenic together with ethynylic and aromatic absorption (page 10 , table 1, run 5). This implies that an intermediate containing allenic and ethylenic groupings exists between the acetylene and aromatic product.

(iv) Diynes and dienynes are aromatised while tetraenes are not. The significant difference in these types of compounds is that

$$\begin{array}{ccccc} HC\equiv CCH_2CH_2CH_3 & \rightleftharpoons & H_2C{=}C{=}CHCH_2CH_3 & \rightleftharpoons & H_3CC\equiv CCH_2CH_3 \\ (76) & & (77) & & (78) \\ 1{\cdot}3\% & & 3{\cdot}5\% & & 95{\cdot}2\% \end{array}$$



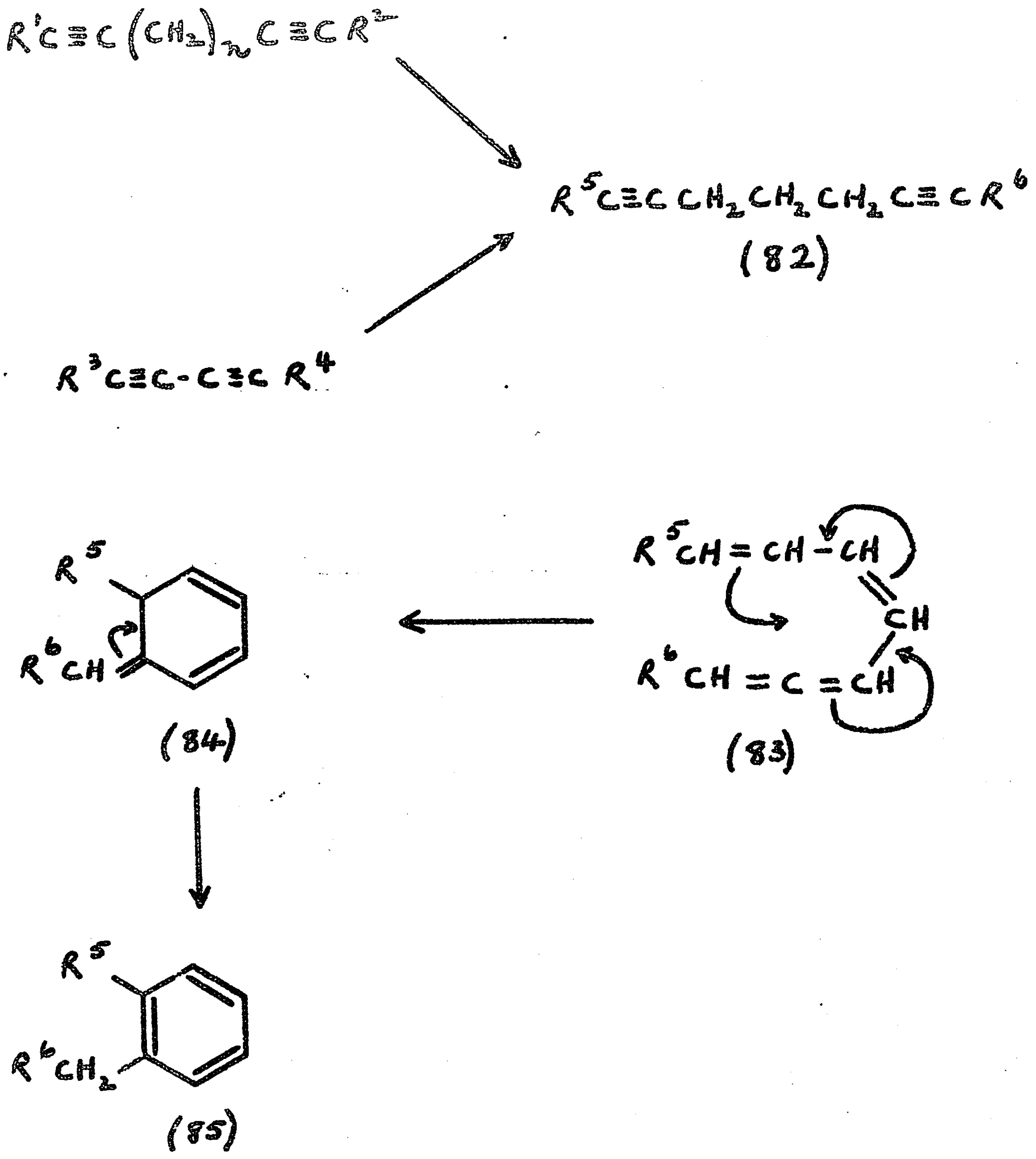
$$\begin{array}{c} HO_2CCH_2C\equiv C{-}C\equiv CCHCO_2H \\ (80) \\ \downarrow \\ HO_2C.CH=CH.CH=CHC\equiv C.CO_2H \\ (81) \end{array}$$

acetylenes can isomerise to allenes while the tetraenes being more stable than allenes, can not. This again supports the contention that allenes play an essential role in the aromatisation process.

(v) The aromatisation of diacetylenes leads to a mixture of mono- or o-disubstituted benzenoid products only. As the chain length of the diyne increases the amount of monosubstituted product decreases and the product which predominates is always the most symmetrical 0-disubstituted isomer.

(vi) Non-aromatic unsaturated compounds are inevitably formed in low yield as by products.

As early as 1888 Favorskii[22] described the isomerisation of but-1-yne to but-2-yne with potassium ethoxide in ethanol, and showed that the allene buta-1, 2-diene was an intermediate. Jacobs[31] in recent years has examined the analogous rearrangement of pentyne with alcoholic potassium hydroxide and found that an equilibrium mixture of pent-1-yne (76), the allene (77) and pent-2-yne (78) was set up as shown. To explain this he proposed the route shown which also allows for conjugated diene (79) formation. Jacobs, however, did not find any diene but Jones and Whiting extending their work on the rearrangement of hydrocarbons[57] to diacetylenic diacids describe the formation of the diene (81) by treatment of the diacid (80) with aqueous



$$HC\equiv C(CH_2)_{17}C\equiv CH$$

(86)

$$\downarrow$$

$$CH_3(CH_2)_6C\equiv C(CH_2)_3C\equiv C(CH_2)_6CH_3$$

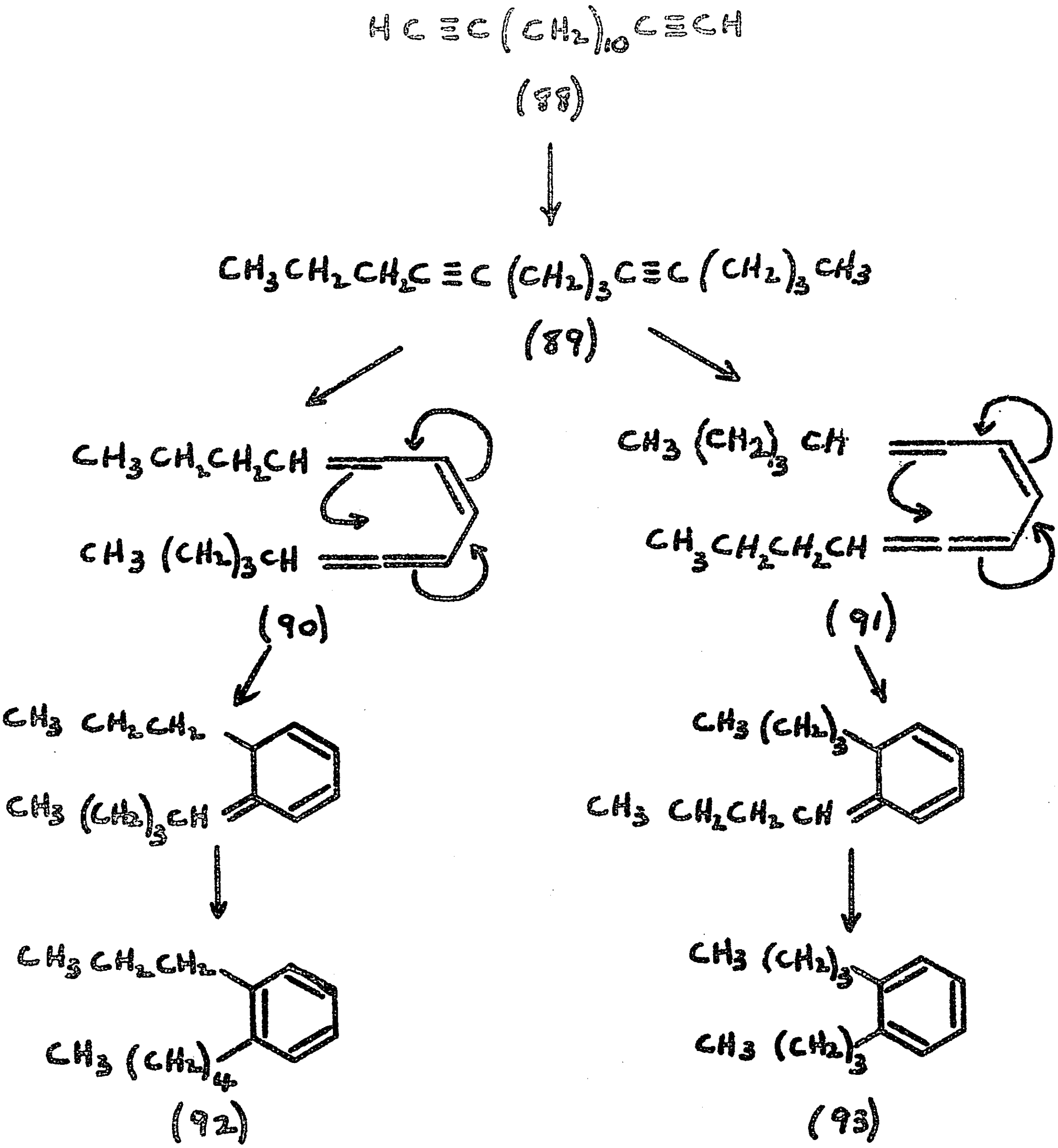
(87)

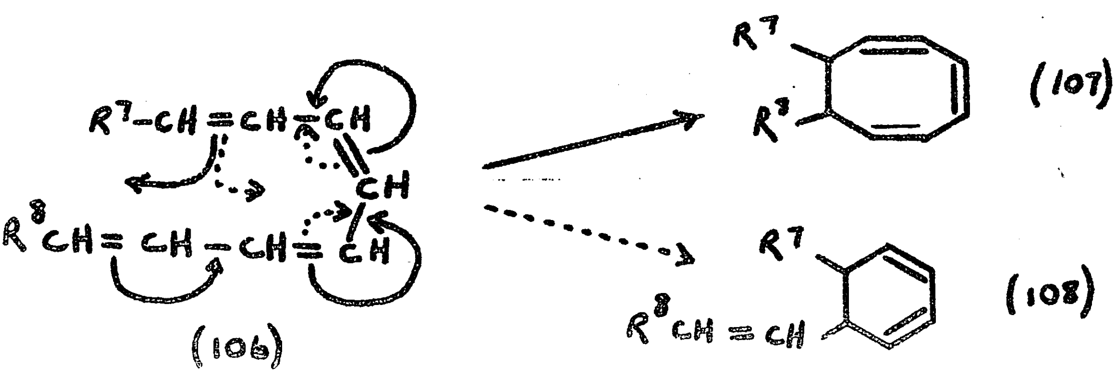
potassium hydroxide.

In the present case it is suggested that the triple bonds move towards or away from each other by this mechanism, as the case may be, until the position (82) is reached in which there are two triple bonds within a seven carbon system. Further rearrangement then gives the conjugated allene-diene system (83) which undergoes an internal Diels-Alder cyclisation to (84) and in turn is isomerised to the 0-disubstituted aromatic system (85). This mechanism accounts satisfactorily for the observations (i) - (iv).

It is surprising that successive prototopic shifts should occur over an extended chain of as many as seven carbon atoms which must be the case if the intermediate (87) is formed from heneicosa - 1, 20 - diyne, and it would be interesting to discover how long the carbon chain must be before the driving force of potential aromatisation becomes ineffective. It is equally surprising that the conjugated diyne system in octa-3, 5-diyne should be disrupted which gives testimony to the compelling force of potential aromatisation.

An explanation for observation (v) that the main product is always the most symmetrically substituted 0-dialkyl benzene follows from this mechanism. In the case of tetradeca - 1, 13-diyne (88), for example, assuming that the triple bonds move

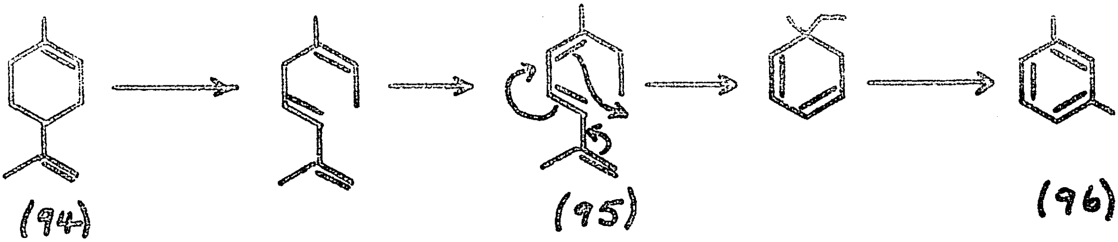

HC≡C(CH2)10C≡CH
(88)
CH3CH2CH2C≡C(CH2)3C≡C(CH2)3CH3
(89)
CH3CH2CH2CH
CH3(CH2)3CH
(90)
CH3(CH2)3CH
CH3CH2CH2CH
(91)
CH3CH2CH2
CH3(CH2)3CH
CH3(CH2)3
CH3CH2CH2CH
CH3CH2CH2
CH3(CH2)4
(92)
CH3(CH2)3
CH3(CH2)3
(93)


R7-CH=CH-CH
A
CH
R8CH=CH-CH=CH
(106)
R7
R8
(107)
R7
R8CH=CH
(108)

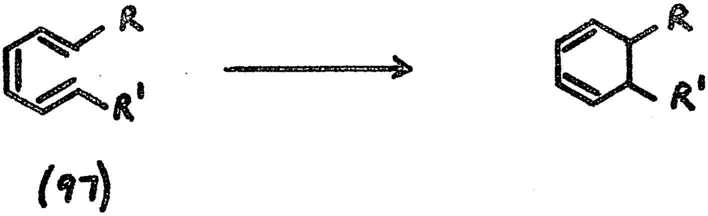
towards one another at approximately the same rate, the unsymmetrical diacetylene (89) will be formed. Aromatisation can then occur either via (90) or (91) giving the unsymmetrical (92) or the symmetrical (93) O-disubstituted benzenes respectively. This explains the predominance of the two most evenly substituted isomers in every aromatisation. The fact that (93) forms the major product might reflect a statistical preference for the formation of intermediate (91) rather than (90).

If some of the diyne isomerised, not to the conjugated dien-allene system (83), but to the conjugated tetraene (106), cyclisation involving eight or six carbon atoms could then give the cyclooctatriene (107) or the cyclohexadiene system (108). This would account for observation (vi) that small amounts of unsaturated compounds, containing cis-double bond absorption in the infrared, inevitably occur as by-products in the isomerisations.

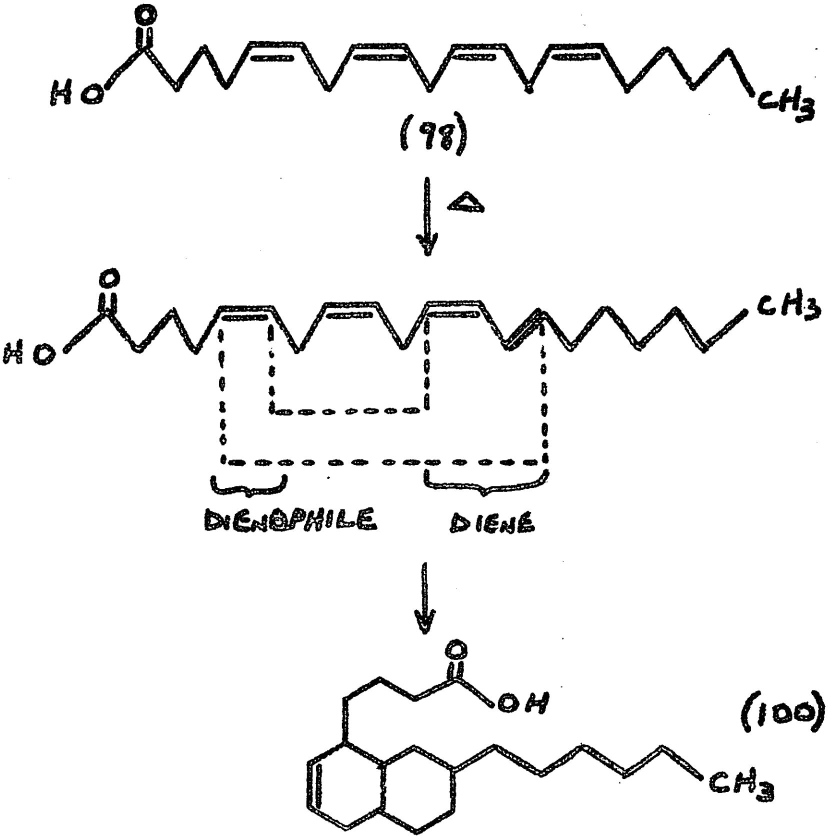
Internal Diels-Alder cyclisations have been proposed before. Pines[58] suggests this mechanism for the pyrolytic aromatisation of limonene (94) by cyclisation of the intermediate (95) to m-xylene (96), and Paschke[59] for the cyclisation of eleostearic acid derivatives (97). In this latter paper Paschke also suggests possible routes for the cyclisation of arachidonic acid (98). One of these routes shown involves initial isomerisation of (98) with heat to the conjugated system (99) containing both a diene



(94) (95) (96)

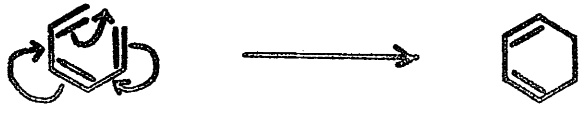


(97)



(98)

(100)



(101) (102)

and a dienophile. Diels-Alder internal cyclisation is then proposed giving the bicyclic acid (100).

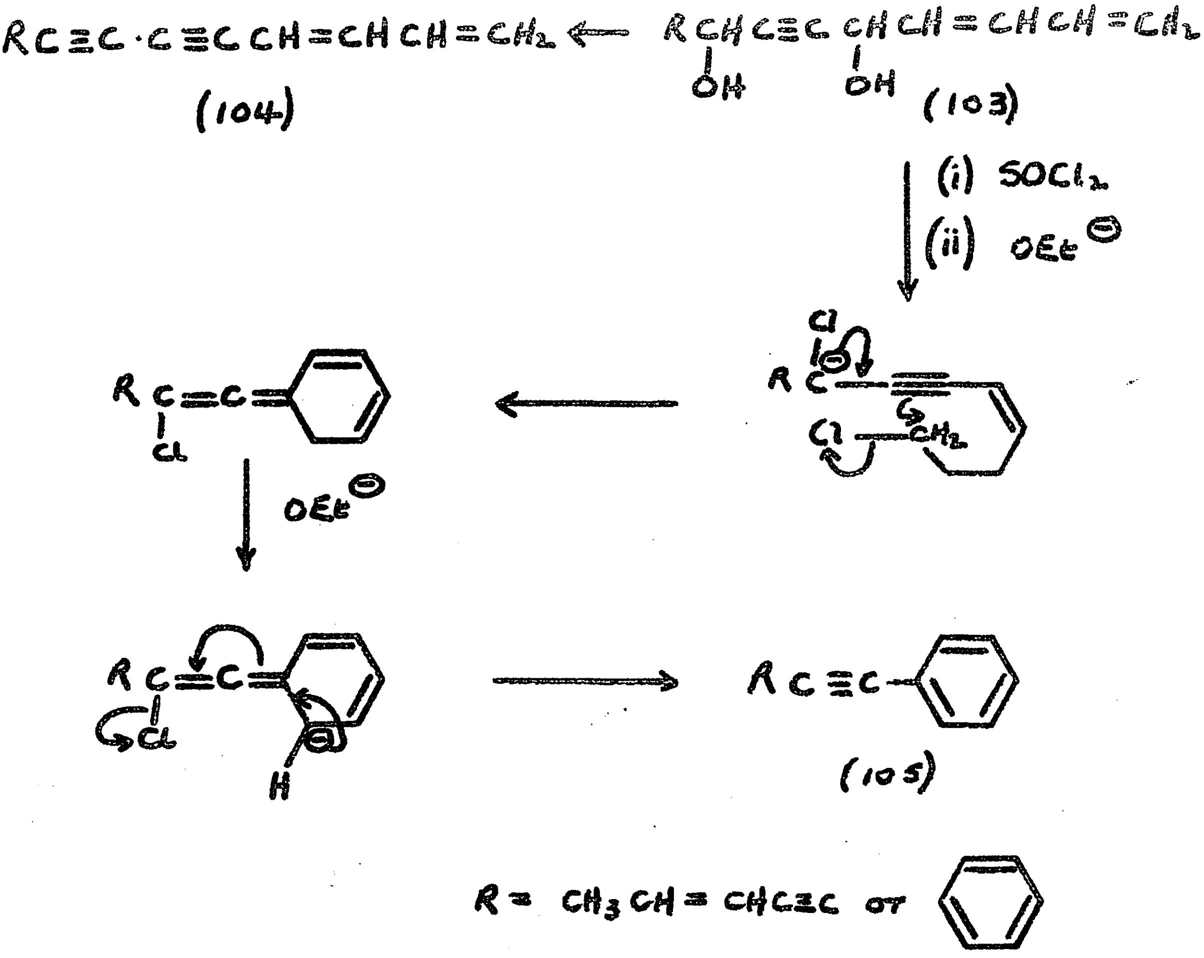
The simplest example of an internal Diels-Alder reaction is described by Alder[60] for the isomerisation of hexatriene (101) to cyclohexadiene (102) at 400°.

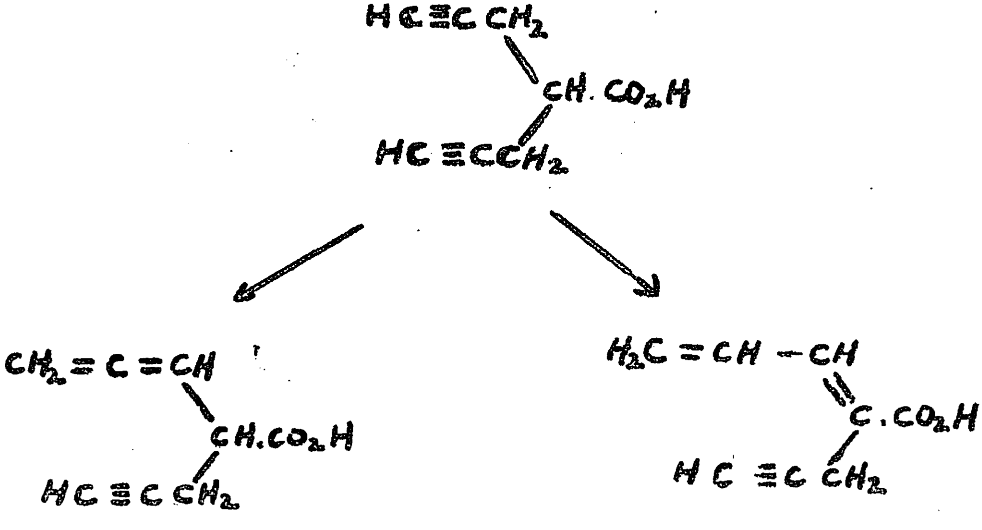
Alternative mechanism.

During their efforts to synthesise trideca -1, 3, 11-triene -5, 7, 9-triyne (104) by chlorination of the diol (103) and subsequent dehydrochlorination with ethoxide Skattebol and Sorenson[61] surprisingly isolated phenylheptenediyne (105). The reaction was later tested with R = phenyl and gave tolan. They suggest the mechanism shown involving cylisation at the dehydrochlorination stage, a mechanism which can hardly apply to aromatisation of diacetylenic hydrocarbons.

Biogenetic Implications.

Sorensen[62] and his colleagues in their significant work on naturally occurring polyacetylenes have pointed out intriguing structural similarities in C_{13} compounds derived from closely related plant species. Thus open-chain compounds, cyclic isomers of the benzenoid series and analogues of the furan and thiophen series are produced by Compositae plants (see table). Bu'Lock[63] has proved that polyacetylenes are synthesised from glucose through acetate and the present work showing the ease


(104)
(103)
(i) SOCl₂
(ii) OEt⊖
OEt⊖
(105)
R = CH₃CH=CHC≡C or

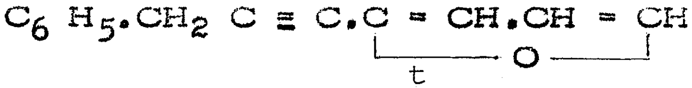

(109)
(110)

of transformation of diacetylenes to benzenoid compounds must surely support the theory[62, 64] that a new benzenoid-ring biosynthesis, alternative to those involving oxygenated cyclic intermediates,[65, 66, 67] such as shikimic acid, is operating.

C_{13} Compounds from Compositae Plants.

$CH_2 = CH.CH = CH.C \equiv C.C \equiv C.C \equiv C.CH \overset{t}{=} CH.CH_2OAc$

$C_6H_5.C \equiv C.C \equiv C.CH = CH.CH_2OAc$



$C_6H_5.CH_2\ C \equiv C.C = CH.CH = CH$ (with $-O-$ joining the C and the last CH)

$CH_2 = CH.C \equiv C.C \equiv C.C \equiv C.C \equiv C.CH \overset{t}{=} CH.CH_3$

$C_6H_5.C \equiv C.C \equiv C.CH \overset{t}{=} CH.CH_3$

$CH_2 = CH.C \equiv C.C \equiv C.C.\equiv C.C \equiv C.C \equiv C.CH_3$

$C_6H_5\ C \equiv C.C \equiv C.C \equiv C.CH_3$

$C_6H_5.C = CH.\underset{S}{CH} = C.C \equiv C.CH_3$

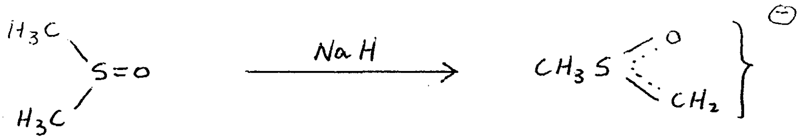
ψ - m - Toluic acid.

It had previously been suggested[21] that Perkin's ψ - m - toluic acid might be an intermediate of the type (109) or (110) between dipropargyl acetic acid and m - toluic acid, and in the hope of detecting such an intermediate, the isomerisation of dipropargyl acetic acid at low temperatures was examined. No isomerisation occurred when the acid was heated with the basic system at 55° for three hours, and the reaction mixture was allowed to stand in the cold for four days. Surprisingly, the infrared spectrum of the product now contained both strong terminal ethynyl and strong aromatic absorption. The ultraviolet spectrum however showed no absorption approaching that expected for a dienic or allenic conjugated acid and was in fact the same as expected of m - toluic acid. Methylation of the product gave an oil with an infrared spectrum in accordance with a mixture of the methyl esters of the dipropargyl acetic and m - toluic acids. The ultraviolet spectrum was identical to that of methyl m - toluate. The components of this mixture were further identified by mixed chromatograms in which there was no trace of a third component.

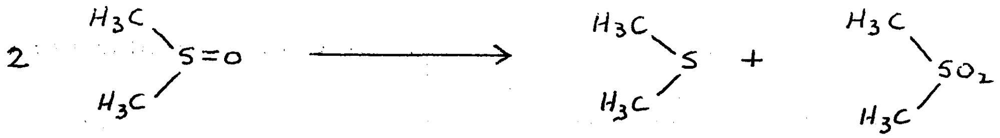
No intermediate in this rearrangement has been detected and the structure of ψ - m - toluic acid remains unknown. The best procedure for any future investigations along these lines would be a direct ultraviolet study of the isomerisation, probably of methyl dipropargyl acetate, as it is actually proceeding.

Dimethyl sulphoxide as a solvent for the base-catalysed isomerisations.

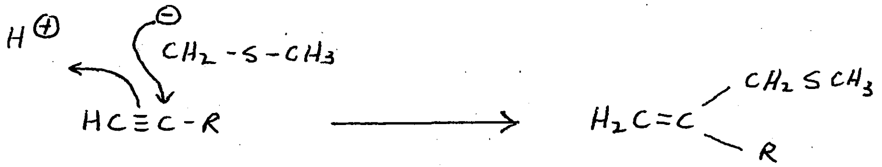
During the course of investigations using potassium t - butoxide in diglyme, attention was drawn to a paper by Cram[68] in which the rate of prototropic rearrangements promoted by t - butoxide is shown to be 10^6 times faster in dimethyl sulphoxide than in t - butanol. It was therefore decided to examine the



(111) (112)



(111) (114) (115)



(116) (117)

$R = CH_2CH{=}CH{-}CH{=}CH_2$

or $CH_2CH_2CH{=}CH{-}CH{=}CH_2$

Table 9.

Infrared spectral data of the products from the attempted isomerisation of hepta-1, 6-diyne using dimethyl sulphoxide as solvent.

Frequency (cm.$^{-1}$)	Assignment.
3010<u>s</u>	H - C = C
1600, 1620<u>w</u>	C = C - C = C
1360<u>m</u>	$C - CH_3$
910, 980<u>m</u>	$H_2C = CH$
705<u>s</u>	- C - S -
690	<u>cis</u> C = C

effects of this system on diacetylenes. On addition of hepta -1, 6 - diyne to a 10% solution of potassium t - butoxide in dimethyl sulphoxide there was an immediate exothermic reaction and intense blue colouration. The infrared spectra of the products (table 9) removed after reaction times of fifteen minutes and thirty-six hours, at room temperature, were identical and there was no trace of either starting acetylene or toluene. A similar spectrum was obtained in the analogous reaction involving octa -1, 7 - diyne, and again there was no trace of aromatisation products ethyl benzene or O-xylene.

Explanations of this anomaly, apparently involving solvent participation, were not readily forthcoming until the recent work of Corey[69] was noted. He found that dimethyl sulphoxide (111) in the presence of the strong base sodium hydride formed the methylsulphinyl carbanion by proton abstraction. Addition of the sulphoxide to the triple bond of the acetylene via this carbanion could be visualised, but would lead to a sulphoxide having very strong absorption in the infrared[70] around 1060 $cm.^{-1}$ This was not the case as the spectrum of the product was in complete agreement with the sulphide, structure (117). A possible explanation is that the dimethyl sulphoxide (111) disproportionated to the sulphide (114) and the sulphone (115) and that addition of this sulphide to a triple bond took place via the corresponding carbanion, as shown, *t* - butoxide replacing the hydride in Corey's work. The incidence of strong conjugated double bond absorption in the spectrum shows that sulphide addition has taken place mainly at one triple bond accompanied by isomerisation at the other.

The actual proof that structure (117) was present was not attempted, as the knowledge that dimethyl sulphoxide was useless as a solvent for the aromatisation of diacetylenes answered the original query.

CONCLUSION

A number of diacelylenic hydrocarbons have been aromatised by potassium t - butoxide in diglyme to mixtures of their mono - and o - disubstituted benzenoid isomers. In these products, the most symmetrical o - disubstituted isomer predominates. Dien-ynes but not tetraenes also undergo the reaction which is general for diacetylenes. The mechanism is believed to involve Diels-Alder cyclisation of a conjugated allene - diene intermediate. ψ - m - Toluic acid has not been isolated and its structure remains unknown. An empirical relationship between the ratio of alkyl substituents in o - disubstituted benzenoid isomers and their G.L.C. retention times is suggested.

The availability of diacetylenes leaves plenty of scope for future uses of this reaction, particularly in the field of hetero-aromatic chemistry.

PART I

EXPERIMENTAL

GENERAL.

Unless otherwise stated, the following experimental conditions apply to parts I, II and III. The infrared spectra were determined on an Infracord spectrophotometer and are corrected to the 1603 cm.$^{-1}$ band of polystyrene. The wave numbers quoted in the 3000 cm.$^{-1}$ region are, however, only believed to be accurate to within 20 cm.$^{-1}$ Accurate infrared spectra were measured on a Unicam model S.P. 100 mark II equipped with gratings. Ultraviolet spectra were determined with a Unicam S.P. 500 quartz spectrophotometer.

The gas-liquid chromatographic (G.L.C.) analyses were run on a Pye-Argon chromatograph with a column (130 x 0.5 cm.) of 85 - 100 mesh celite using 5% Apiezon 'L' as the stationary phase. The relative amounts of eluates were based on the measurement of peak areas by means of a planimeter; the mean of six such determinations being taken. The quantitative results are therefore dependent on uniform response by the β - ionising detector.

In analytical G.L.C.s, the term 'mixed chromatogram' means that a mixture of known and unknown compounds was run and that one peak was obtained with an increase in area corresponding to sum of the areas of the two compounds when run separately.

Woelm alumina, standardised by Brockmann's method to grade V, was used for alumina chromatography. The light petroleum used had b.p. 60 - 80°.

Melting points were taken on a Kofler hot-stage and are corrected. The following terminal diacetylenes were prepared by the method of Bader *et al.*[37] for octa-1, 7-diyne by the reaction of sodium acetylide with the corresponding , α,ω - dibromoalkane. After an explosion during the distillation of hepta-1, 6-diyne, a little hydroquinone was added to the acetylenes before distillation.

Hepta -1, 6 - *diyne* from sodium (118 g., 5.1 mol.), liquid ammonia (1800 ml.) and 1, 3-dibromopropane [38] (252.5 g., 1.25 mol.), as a colourless oil (32.4 g., 28%), Yield decreased by explosion during distillation. b.p. 112-116°/760 mm., n_D^{25} 1.4434, (111.5°/760 mm., n_D^{20} 1.4423).[36] Redistilled, b.p. 40 - 42°/37 mm., n_D^{22} 1.4424, $\nu_{max.}^{film}$ 3240vs, 2100m (-C≡C-), 1930w (allene) and 1630w cm.$^{-1}$. The G.L.C. of this product showed no dibromide and only trace amounts of olefin.

Nona -1, 8 -*diyne*[17, 40] from sodium (10 g., 0.44 mol.), liquid ammonia (150 ml.), 1, 5-dibromopentane (24.4 g., 0.11 mol.), as a colourless oil (8.26 g., 65%), b.p. 50°/25 mm., $n_D^{22.5}$ 1,4500, (b.p. 68°/29 mm., n_D^{20} 1.4500),[17] $\nu_{max.}^{film}$ 3250, 2105 cm.$^{-1}$.

Deca -1, 9-*diyne* from sodium (10 g., 0.44 mol.), liquid ammonia

(150 ml.) and 1, 6-dibromohexane (25.9 g., 0.11 mol.), as a colourless oil (6.9 g., 49%), b.p. 66 - 68°/13 mm., n_D^{21} 1.4523, (b.p. 78 - 80°/29 mm., n_D^{20} 1.4528),[17] $\nu_{max.}^{film}$ 3250, 2110 cm.$^{-1}$.

The following terminal diynes were prepared by other routes. Hexa -1, 5 - diyne was prepared by the method of Raphael and Sondheimer.[41] Diallyl (39.6 g., 0.48 mol.) and bromine (158.4 g., 0.99 mol.) gave 1, 2, 5, 6- tetrabromohexane (130 g., 68%) recrystallised from petrol, m.p. 47-49°, 55-57°. The isomers were not separated.

Dehydrobromination of 1, 2, 5, 6 - tetrabromohexane (100.6 g., 0.25 mol.) with sodamide (from sodium, 46 g., 2 mol.) in liquid ammonia (600 ml.) gave hexa -1, 5-diyne as a colourless oil (9 g., 45%) distilled under nitrogen,* b.p. 75-80°, n_D^{20} 1,4374, (b.p. 87-88°, n_D^{23} 1.4380),[41] $\nu_{max.}^{film}$ 3280s, 2920m, 2120m cm.$^{-1}$.

Heneicosa -1, 20-diyne (57) was prepared by the route shown opposite page 11 .

Dibromoundecylenic acid (51).[47]

A solution of bromine (86 g., 0.54 mol.) in petrol (35 ml.) was added over two hours with stirring and cooling to undecylenic acid (50) (97.5 g., 0.54 mol.) in petrol (250 ml.). Stirring was continued for a further two hours and the mixture allowed to stand overnight. Removal of the solvent gave the

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* Distillation carried out in a stream of nitrogen. B.p.s from these distillations are therefore low and over a range of ca. 5°

dibromide (148.5 g., 82%), m.p. 37-38°.

Undec - 10 - ynoic acid (52) [47]

Dibromoundecylenic acid (51) (113.5 g., 0.36 mol.) was halved and each portion heated at 160° with potassium hydroxide (86 g.) in water (52 ml.) for four hours, allowed to stand overnight at room temperature and then heated again for a further four hours. The reaction mixtures were cooled, dissolved in water (750 ml.), acidified to Congo Red with 6 N sulphuric acid, extracted with ether (4 x 125 ml.) and the extracts combined and dried with magnesium sulphate. Removal of the solvent and distillation gave the acid (46.8 g., 78%), b.p. 124-128°/0.25 mm., m.p. 43° (b.p. 178-184°/15 mm., m.p. 43°)[47, 48]

Undec - 10 - ynoyl chloride (53).

Undec - 10 - ynoic acid (52) (40 g., 0.22 mol.) was heated with thionyl chloride (40 g., 24.4 ml., 0.33 mol.) on a water bath at 60° for two hours and then on a steam bath until evolution of sulphur dioxide and hydrogen chloride ceased (a further two and a half hours). Excess thionyl chloride was then removed under water pump pressure and the product distilled to give the chloride (38 g., 87%), b.p. 110-116°/0.3 mm., $\nu_{\text{max.}}^{\text{film}}$ 3280m, 2115w, 1800vs (acid chloride), 735s and 680s cm.$^{-1}$ (chloride).

Ketene dimer of undec - 10 - ynoyl chloride (55).[49]

The chloride (53) (17.35 g., 0.087 mol.) was split into four equal portions each of which was mixed with triethylamine (2.71 g., 0.027 mol.) in dry benzene (60 ml.). The reaction mixtures were allowed to stand overnight in tightly stoppered flasks. They were then combined and vigorously stirred for three hours. The mixture was then acidified with 6N sulphuric acid, water (ca. 100 ml.) added and extracted with ether (4 x 100 ml.). The extracts were washed with water, dilute salt solution, dried and decolourised with magnesium sulphate/charcoal and the solvent removed to give a yellow oil $\nu^{film}_{max.}$ 3290, 2110, 1870 and 1820 cm.$^{-1}$ (β-lactone), which was decomposed immediately.

Decomposition of the Ketene dimer[50]

The yellow oil was mixed with ethanol (125 ml.), water (10 ml.) and potassium hydroxide (13 g.) and after standing at room temperature for forty-eight hours, was refluxed for four hours. Cooling then gave crystals of heneicosa -1, 20-diyn -11-one (56) (13.6 g., 41.3% from undecynoic acid). Recrystallised as white plates m.p. 46-47° from aqueous methanol, $\nu^{film}_{max.}$ 3270m, 2110w, 1700s and twin peaks at 722m and 728m ($[CH_2]_n$). (Found: C, 83.41; H, 10.99. $C_{21}H_{34}O$ requires C, 83.38; H, 11.33%). The infrared spectrum showed weak absorption between 1600-1640 cm.$^{-1}$ indicating that some isomerisation had taken place. This was unavoidable and was removed at a later chromatography stage.

Clemmenson Reduction of heneicosa - 1, 20-diyn - 11 - one (56)

The zinc amalgam was prepared by shaking zinc dust (10 g.), mercuric chloride (1 g.), concentrated hydrochloric acid (1 ml.) and water (15 ml.) together for five minutes. The supernatant liquid was decanted, the amalgam washed several times with water and used in the reductions below.

Reduction without a co-solvent: The zinc amalgam was covered with water (7.5 ml.) and concentrated hydrochloric acid, the ketone immediately added and the mixture refluxed for eighty-seven hours. The infrared spectrum of an aliquot at this point showed considerable carbonyl absorption, so the reaction was repeated for a further eighty hours, extracted with 40-60° petrol (4 x 50 ml.), dried with magnesium sulphate and the solvent removed to give a white low melting solid (1.52 g.). Chromatography of this product on grade V alumina (50 g.) gave three fractions.

Fraction 1. (490 mg.), elution with petrol, $\nu_{max.}^{melt}$ 3300w, 1630m, 990s (-CH = C-), 915s cm.$^{-1}$ (= CH_2) (Mixture of en-ynes).

Fraction 2. (280 mg.), elution with petrol, $\nu_{max.}^{melt}$ 3300s, 1630w, 990w, 915w cm.$^{-1}$ (mixture of required diyne and en-yne)

Fraction 3. (59 mg.), elution with 50/50 petrol-benzene, $\nu_{max.}^{melt}$ 3300w, 1700s, 1630m, 990s, 915s cm.$^{-1}$ (mixture of en-yn-ones).

Fraction 2 was rechromatographed on grade V alumina (50 g.), elution with petrol, and two main fractions obtained.

Fraction 2 (i), (152 mg.), $\nu^{\text{melt}}_{\text{max.}}$ 3300s, 1630w cm.$^{-1}$ (mixture of diyne and en-yne).

Fraction 2 (ii), (82 mg.), no olefinic or carbonyl absorption and the infrared spectra is as expected for heneicosa -1, 20-diyne with a singlet at 735ms cm.$^{-1}$ ($-[CH_2]_n-$)

Thus isomerisation during reduction renders this method completely impracticable.

Reduction with a co-solvent present: The reduction was performed on the ketone (500 mg.) with the same reducing system as above but containing dioxan (ca. 10 ml.) The mixture was refluxed for ninety minutes, more concentrated hydrochloric acid (5 ml.) added and refluxing continued for a further ninety minutes. The infrared spectrum of an aliquot showed carbonyl absorption, so the reduction was allowed to continue for a further three hours. Extraction as above gave a product (500 mg.) containing a little olefin which removed by alumina chromatography (grade V, 50 g.) to give the required heneicosa -1, 20-diyne (57) as a white wax (239 mg., 50%), m.p. 47-48° (from methanol), $\nu^{\text{melt}}_{\text{max.}}$ 3300s, 2110w-m, 725s cm.$^{-1}$ (Found: C, 87.28; H, 12.66. $C_{21}H_{36}$ requires C, 87.42; H, 12.58%). Analytical G.L.C. at 196°, Argon flow rate of 49 ml./min. gave substantially one peak R_T34.4 min.

The reduction time is very crucial and better results would have been obtained if the reaction time in the above reduction had been about four and a half instead of six hours, unchanged ketone being more readily separable from the diyne than any of the isomerisation products.

Nona -2, 7 - *diyne* was prepared from hepta -1, 6-diyne by the method of Henne and Greenlee.[36] Thus a preparation involving sodium (3 g., 0.13 mol.), liquid ammonia (100 ml.), hepta -1, 6-diyne (4.5 g., 0.049 mol.) and methyl bromide (*ca*. 12 ml.) gave nona -2, 7-diyne as a colourless liquid (3.8 g., 67%), b.p. 67°/11 mm., n_{D}^{24} 1.4660, (180°/760 mm., n_{D}^{20} 1.4674),[36] $\nu_{max.}^{film}$ 2060w cm.$^{-1}$

Satisfactory results were only obtained when methyl bromide was substituted for the recommended methyl iodide. The bromide, a gas at room temperature, was simply bubbled into the disodioacetylide suspension in liquid ammonia where it condensed.

Octa -3, 5-*diyne* [43] was prepared by the addition of ethyl iodide to the disodium salt of butadiyne, itself prepared in situ by the dehydrohalogenation of 1, 4-dichlorobut -2 -yne with sodamide in liquid ammonia, as described by Jones and Whiting.[43]

1, 4- *Dichlorobut* - 2 - *yne* was prepared as described by Johnson [42] by chlorination of but-2-yne -1, 4-diol (25 g., 0.29 mol.) with thionyl chloride (50 ml.) in pyridine (45 ml.). The chloride was obtained as a colourless oil (21.35 g., 63%), b.p. 58°/12 mm., n_D^{21} 1.5050, (b.p. 68°/17 mm., n_D^{20} 1.5072) [42]

Octa -3, 5-*diyne* from 1, 4 - dichlorobut - 2 - yne (10 g., 0.083 mol.), sodamide (from sodium 7.7 g., 0.33 mol.), liquid ammonia (150 ml.) and ethyl bromide (19.6 g., 0.22 mol.) as a colourless oil (4.52 g., 54%), b.p. 54-56°/17 mm., n_D^{20} 1.4931, (n_D^{22} 1.4928), [43] $\nu_{max.}^{film}$ 2150w, 2180w cm.$^{-1}$
Ethyl bromide was found to be a more satisfactory ethylating agent than the recommended ethyl iodide.

Cyclotetradeca -1, 8-*diyne* [45,46] Nona -1, 8-diyne (1 g., 0.0083 mol.) in dry ether (35 ml.) was added over fifteen minutes with vigorous stirring to a solution of sodamide (from sodium, 0.4 g., 0.017 mol.) in liquid ammonia (1 l.), and after two hours 1, 5-dibromopentane (1.92 g., 0.0084 mol.) in dry ether (100 ml.) was added over a further two hours. This mixture was stirred overnight, cotton-wool lagging being used as insulation, ammonium chloride (*ca.* 2g.) and more ether (200 ml.) added and the ammonia allowed to evaporate off. Water (100 ml.) was then added, the ether layer separated and the aqueous layer extracted with ether (3 x 50 ml.). The ethereal extracts were combined, washed with 2N sulphuric acid (100 ml.), saturated sodium carbonate solution (100 ml.), water (100 ml.) and dried with magnesium sulphate. Removal of the solvent gave an oily yellow solid which was immediately chromatographed through grade V alumina (40 g.) to give the diyne as colourless plates (0.536 g., 34%), m.p. 97.5-98°/ from aqueous methanol . (Found: C, 89.08; H, 10.62. Calc. for $C_{14}H_{20}$: C, 89.29; H, 10.71%).

ISOMERISATIONS.

Preliminary isomerisations of hepta -1, 6-diyne.

The efficiency of the various basic systems listed in table 1, page 10 to catalyse prototropic rearrangement of hepta -1, 6-diyne to toluene were determined by assessing the relative amounts of terminal acetylene, allene, ethylene, vinyl ether and toluene present in the infrared spectra of the products obtained by refluxing the diyne with these basic systems for suitable times. The results are tabulated in table 2. The best system for the aromatisation was 10% potassium t-butoxide in diglyme.

Isomerisation of Diacetylenes

In every case the aromatisation was accomplished by refluxing the diyne with 10% potassium t-butoxide in diglyme (3 g. of butoxide used for every 0.5 g. of diyne). The t-butoxide (from dry t-butanol) was pre-treated before use by heating at 160° under oil pump pressure until sublimation started. The diglyme was dried by distillation from sodium before use and the isomerations were performed under a stream of dry nitrogen. The reaction products were worked up by initial dilution with water, extraction with n-pentane, washing at least six times with water, to effect removal of the diglyme, drying with magnesium sulphate and removal of the solvent under water pump pressure.

G.L.C. analysis of the products was carried out on a Pye-Argon chromatograph. The areas were measured with a planimeter and the mean of six such readings taken. The inaccuracy in reproducibility of the Pye-Argon apparatus is ±7% and since compounds of the same type were generally examined differences in the β-ionisation detector response should be small. Inaccuracies are therefore not believed to be greater than ±7%.

Alkaline permanganate oxidation of the aromatic products.

A typical example is the oxidation of O-xylene:-

O-xylene (0.126 g., 0.0012 mol.) was refluxed with *t*-butanol (5 ml.), water (7 ml.), sodium carbonate (*ca.* 0.5 g.) and potassium permanganate (0.8 g., 0.005 mol.) for four hours. The mixture was then cooled, acidified with 6N sulphuric acid and refluxed for a further thirty minutes. Solid sodium bisulphite was then added to remove precipitated manganese dioxide, and the resulting clear solution extracted with ether (3 x 20 ml.), the extracts washed with saturated salt solution and dried with magnesium sulphate. Removal of the solvents gave phthalic acid (0.174 g., 88%) sublimed at 100-140°/0.1 mm. as phthalic anhydride, m.p. and mixed m.p. 131°.

All oxidations of the isomeration products were carried out in this way generally on *ca.* 100 mg. of product and using an excess of permanganate. Resulting mixtures of benzoic and phthalic acids were easily separated by sublimation; the former subliming at a much lower temperature.

Attempted isomerisation of hexa-1, 5-diyne (table 2, run 1)

Aliquots removed from an attempted isomerisation of hexa -1, 5-diyne (0.5 g.) after reaction times of one, three and seven hours had substantially the same infrared spectra, $\nu^{\text{film}}_{\text{max.}}$ 3010 (H - C = C -), 1630 and 1570 (conjugated double bond), 1360 (- CH_3), 1200 - 1050 (ether) and 890 cm.$^{-1}$ (t-butoxide). The product after seven hours was refluxed with twice its volume of 3N hydrochloric acid, extracted with ether, washed with sodium bicarbonate, water and dried with magnesium sulphate to give a brown oil $\nu^{\text{film}}_{\text{max.}}$ 3350 (intermolecular bonded OH), 1710 - 1590 broad absorption with peaks at 1710, 1680, 1640 and 1590 cm.$^{-1}$ (conjugated diene-one).

The hydrolysed product gave a dark red precipitate from Brady's solution which darkened rapidly an attempted crystallisation from ethanol, acetic acid, and ethyl acetate giving insoluble residues. Aromatisation of the hexa-1, 5-diyne had obviously not taken place and the product was not investigated further.

Isomerisation of hepta -1, 6 - diyne (table 2, run 2).

Treatment of the diyne with the basic system at 130° for fifteen minutes gave a product $\nu^{\text{film}}_{\text{max.}}$ 727s cm.$^{-1}$ (H-C ≡ C) completely absent.

An isomerisation of the diyne (1 g.) at reflux for four hours gave a product (0.87 g.). This product (0.76 g.) on oxidation with permanganate gave benzoic acid (0.11 g.), m.p. and mixed m.p. 122°. Comparison with an identical oxidation of toluene (1 g.), in which the yield of benzoic acid was 84%, indicated that the yield of toluene from hepta -1, 6-diyne was 22%.

<u>Yield of toluene by infrared analysis</u> was determined by comparing the optical density of the γ--CH band at 727 cm.$^{-1}$ produced by carbon disulphide solutions of toluene and isomerised product. The results are given below:

Toluene (mg.) in 10 ml. of CS_2 solution	Optical density
16.24	1.9
8.82	1.03
5.68	0.658
Product at same dilution	
22.4	0.7

22.4 mg. of product therefore contain 6.05 mg. of toluene corresponding to a yield of 35% from the diyne.

<u>Isomerisation of octa</u> -1, 7-<u>diyne</u> (table 2, page , run 3)

The diyne (0.553 g.) was refluxed with the basic system and an aliquot (5 ml.), removed after one hour, was completely free of terminal acetylene. The reaction was allowed to continue for a further six hours and gave, on working up, an oil (0.4 g.), $\nu_{max.}^{film}$ 745vs, 700s cm.$^{-1}$ (γ - CH of *O*-xylene[71] 741 cm.$^{-1}$, of ethyl benzene[72] 696 cm.$^{-1}$

Permanganate oxidation of the product.

The product (0.39 g.) on oxidation with alkaline permanganate gave a white solid (0.42 g.) which sublimed to give mainly phthalic anhydride, m.p. and mixed m.p. 131-132°, and a trace of benzoic acid m.p. 122°. Accounting for a yield of 88% (from the identical oxidation of *o*-xylene) and the presence of 60.8% of *o*-xylene in the product, by quantitative infrared analysis, this oxidation result indicates the presence of 22% of ethyl benzene in the isomerisation product. The yield of aromatic isomers from octa -1, 7 - diyne is therefore 72%.

Isomerisation of octa -3, 5-diyne (table 2, page , run 4)

The diyne (0.5 g.) was refluxed with the basic system and an aliquot (5 ml.), removed after twelve hours, showed strong γ-CH aromatic infrared absorption. After fifteen hours the reaction was worked up to give the product (0.31 g.), b.p. 146-149°/760 mm., n_D^{26} 1.4995 (Ethyl benzene, b.p. 136°; *o*-xylene, b.p. 144°, n_D^{20} 1.5058) Infrared spectrum identical to that of the product from octa -1, 7 - diyne.

Permanganate oxidation of the product (0.102 g.) gave a white powder (0.115 g.) sublimed to benzoic acid m.p. and mixed m.p. 119.5 - 121°, and phthalic anhydride m.p. and mixed m.p. 131-132°.

Analytical G.L.C. of the product (table 3, page 14) showed that it consisted of three components, two of which were identified by mixed chromatograms as ethyl benzene and *O*-xylene as 28 and 64% of the product. The third component is unknown. The yield of aromatic isomers from the diyne was therefore 68%.

Isomerisation of Nona -1, 8 - *diyne*. (table 2, page 12, run 5)

The diyne was refluxed with the basic system for six hours. The infrared spectra of aliquots (4.6 and 5 ml.) removed after one and five hours, were identical to that of the final product (0.27 g.), $\nu_{\text{max.}}^{\text{film}}$ 795, 756, 732 (γ- CH of *O*-ethyl toluene) and 740, 698 cm.$^{-1}$ (γ- CH of *n* - propyl benzene).

Permanganate oxidation of the product.

(0.12 g.) gave a white solid (0.13 g.) which sublimed at 160°/760 mm. to benzoic acid, m.p. 120°, and phthalic acid m.p. 197° (indefinite). Assuming that the product is mainly *o*-ethyl toluene and that the yield in oxidation is *ca.* 88%, product contains *ca.* 89% of *o*-ethyl toluene.

Analytical G.L.C. of the product (table 4, page 15) revealed the presence of three peaks present as 6, 17 and 77% of the product. The first of these was identified by a mixed chromatogram as *n* - propyl benzene and the last, from the infrared, is probably *O*-ethyl toluene. The yield of aromatic isomers from nona -1, 8-diyne is therefore 69%.

Isomerisation of nona -2, 7-diyne (table 2, page 12, run 6)

The diyne (0.5 g.) after seven hours gave an oil (0.35 g.). The infrared spectra of the product and that of an aliquot (4.7 ml.), removed after one hour, were identical to that of the isomerisation product of nona -1, 8 - diyne above.

Permanganate oxidation of the product.

(0.35 g.) gave a brown powder (0.4 g.) which sublimed to benzoic acid, m.p. 120°, and phthalic anhydride m.p. and mixed m.p. 131-131.5°. Assuming again that the yield in oxidation was 88% and that the main component was o-ethyl toluene, this oxidation indicates that the product contains 94% of o-ethyl toluene. Comparing this with the value (89%) obtained above, the yield of aromatic isomere of nona -2, 7 - diyne is ca. 70%.

Isomerisation of deca -1, 9 - diyne (table 2, page 12, run 7)

This diyne (2.6 g.) on treatment under isomerisation conditions for eighteen hours gave an oil (1.72 g.), $\nu^{\text{film}}_{\text{max.}}$ 790w, 745s, 710m and 700w cm.$^{-1}$ (γ - CH vibrations in a mixture of o-disubstituted benzenoid isomers; 700 cm.$^{-1}$ possibly mono-substituted isomer).

Analytical G.L.C. of product (table 6, page 17) showed one peak with a shoulder (ca. 5%). The retention times of the shoulder and n - butyl benzene were the same and differed from that of the main peak by only 0.6 minutes. A mixed chromatogram with n - butyl benzene therefore only broadened the main peak without separation. The main peak is presumed to consist of o-n-propyl toluene and o-diethyl benzene as ca. 95% of the product. The yield of aromatic isomers from deca -1, 9-diyne is then ca. 66%.

Isomerisation of tetradeca -1, 13-diyne (table 2, page 12, run 8)

Isomerisation of this diyne (0.5 g.) for eighteen hours gave an oil (0.37 g.), $\nu^{\text{film}}_{\text{max.}}$ 750 br.s, 710w cm.$^{-1}$

Permanganate oxidation of the product (0.3 g.) gave a grey powder (0.1 g.) sublimed as phthalic anhydride m.p. and mixed m.p. 131.5 - 132°. Assuming a yield of 80%, this oxidation corresponds to 48% of O-disubstituted C_{14} aromatic isomers in the product.

Analytical G.L.C. of the product (fig. 1, page 17) revealed the presence of at least six components two of which, occurring as 52 and 23% of the product, were separated by preparative G.L.C. on the Pye-Argon apparatus using a 10% Apiezon 'L' column (130 x 1 cm.) at 115° and an Argon flow-rate of 0.15 l./min. A series of 10 μl. samples were injected on to the column and the separated fractions were trapped in a U-tube immersed in a dricold/acetone mixture. Although considerable trouble was taken to ensure that no moisture entered the traps, the collected fractions were inevitably wet, moisture presumably entered during the short periods just before and after collection when the drying tubes were removed. The presence of moisture made quantative infrared analysis impossible and the solutions in carbon disulphide were dried and diluted until suitable spectra were obtained. The Unicam infrared spectra of these fractions are reproduced in figs. 2 and 3. The mass spectra (figs. 4 and 5) of these fractions showed that the component present as 52% was O-bibutyl benzene (64) and that in 23% as o-n-pentyl-n-propyl benzene (65). The component with a longer retention time than these two and present as 7% of the mixture was probably O-n-hexylethyl benzene. The yield of these three isomers was 62% from tetradeca -1, 13-diyne.

Isomerisation of heneicosa -1, 20-diyne (57) (table 2, page 12, run 9)

Isomerisation of this diyne (180 mg.) for twenty-four hours gave an oil (153 mg.), $\nu^{\text{film}}_{\text{max.}}$ 980, 960 (trans double bond), 753, 725, 715 cm.$^{-1}$ (mixture of O-disubstituted benzenes).

Hydrogenation of the isomerisation product (150 mg.) in cyclohexane (25 ml.) over 10% palladium/charcoal resulted in the uptake of 12 ml. of hydrogen corresponding to the hydrogenation of one double bond equivalent. This corresponds to a yield of aromatic compounds of 75% provided that the reduced materials were non-cyclic. The product, an oil, now had peaks in the infrared at 2670w, 810w (cycloalkane ?), and 753, 725 cm.$^{-1}$ The G.L.C. of the hydrogenated product (fig. 6) contained eight peaks, five of which were assigned to isomers n-heptyl-n-octyl benzene (67) to n-propyl-n-dodecyl benzene (71) as 73% of the mixture. The yield of aromatic isomers from the mixture was 64%. Repeated attempts to separate the main peaks by preparative G.L.C., using the Gas-liquid Chromatobraphic Company's apparatus with 10% Apiezon 'L' column, failed because of continual bleeding of the stationary phase.

Isomerisation of cyclotetradeca -1, 8-diyne (table 2, run 10)

This diyne (150 mg.) after sixteen hours gave a colourless oil (133 mg.), $\nu^{\text{film}}_{\text{max.}}$ 810m, 780m, 768m, 746s, 728m and 696w cm.$^{-1}$ Analytical G.L.C. (table 7, run 3) showed four peaks X, Y, Z and starting material in 2, 20, 69.4 and 8.4% respectively. The last peak was identified by mixed chromatograms (table 7, runs 1, 2, 4). Complete hydrogenation of the product (110 mg.) gave the product as an oil (100 mg.), $\nu^{\text{film}}_{\text{max.}}$ 780, 768, 746, 728 and 696 cm.$^{-1}$ Analytical G.L.C. (table 7, run 5) showed that the cyclotetradeca -1, 8-diyne had been reduced quantatively to, presumably, cyclotetradecane and unknown X to a mixture of two new unknowns. The retention of components Y and Z remained unchanged. Attempts to separate the mixture by alumina chromatography failed. Component Z is probably benzocyclodecene obtained in 62% yield from the diyne.

Isomerisation of bis-ethynylcyclohex-1-ene (table 2, run 11).

The diyne (400 mg.) after fifteen hours gave a brown oil (166 mg.), G.L.C. analysis and mixed chromatogram with

1, 4-diphenyl butane showed one peak at 153.5°, Argon flow-rate 40 ml./min., R_T 63.6 min. Alumina chromatography gave a colourless low melting solid, infrared spectrum identical to that of 1, 4-diphenylbutane. The yield of diphenyl butane was 42%.

Isomerisation of dipropargyl acetic acid (table 8, run 1)

The diyne (23 mg.) after five hours gave a white solid (160 mg.), recrystallised from water as m-toluic acid, m.p. and mixed m.p. 110°.

Ethyl arachidonate (72) (table 8, run 2)

The ester (880 mg.) was isomerised for eighteen hours and the products extracted from basic and acidic solutions. Basic extracts (180 mg.) of ester $\nu_{\text{max.}}^{\text{film}}$ 1640-1600m (conjugated double bonds), 960m (trans-double bonds), 710w., br. (cis-double bond). The spectrum was contaminated with diglyme and the product was washed a further six times with water and dried over magnesium sulphate overnight. The infrared spectrum of the product now contained little double-bond but weak-medium hydroxyl absorption (3500 cm.$^{-1}$). Hydration of the double bond system had apparently occurred.

The acid fraction (500 mg.), $\nu_{\text{max.}}^{\text{film}}$ 1640 -1590w, 940w, 710w, cm.$^{-1}$ (conjugated system again), decomposed to a tar on standing in the fridge. In both extracts there was no trace of aromatic compounds. The experiment was thrice repeated and the same results obtained.

Isomerisation of octadeca -9, 12-dien-6-ynoic acid (73) (table 8, run 3)

This acid (95 mg.) after eight hours gave an acidic product (80 mg.) as a brown oily solid, $\nu_{max.}^{film}$ 1600w, 1500w, 960m (**trans**-double bond), 750m and 725m cm.$^{-1}$ (aromatic γ - CH). Permanganate oxidation of the product (115 mg.) have phthalic acid (52 mg.), m.p. and mixed m.p. 130-131°. (as the anhydride).

Attempted detection of _ - m toluic acid.

Dipropargyl acetic acid (700 mg.) was heated with the basic system at 55°. Aliquots removed at intervals over three hours showed no indication of isomerisation. The reaction mixture was heated for a further three hours and then allowed to stand at room temperature for four days to give an oil $\nu_{max.}^{film}$ 3230s ($H - C \equiv C$), 750s cm.$^{-1}$ (aromatic γ - CH), qualitative ultraviolet $\lambda_{max.}^{EtOH}$ 210m, 232s, 278w mμ .

The product was methylated with diazomethane as follows:- 50% aqueous potassium hydroxide (6 ml.) and ether (20 ml.) were mixed and cooled in ice. Nitrosomethylurea (2 g.) added with shaking and the ethereol layer decanted into a solution of the product in ether until a permanent yellow colouration persisted. The mixture was allowed to stand overnight, washed with saturated sodium carbonate, salt solution and dried over magnesium sulphate. Removal of the solvent gave from the diyne (700 mg.), without removing aliquots, the ester (410 mg.),

$\nu_{\text{max.}}^{\text{film}}$ 3250s (H − C ≡ C), 1740vs (ester), 750s cm.$^{-1}$ (aromatic γ − CH in methyl m-toluate), $\lambda_{\text{max.}}^{\text{EtOH}}$ 207 (ε 1700), 234 (1560), 280 mμ (540) identical to that of methyl m-toluate. Analytical G.L.C. showed two components identified by mixed chromatograms as methyl dipropargyl acetate R_T 4.2 min., and methyl m-toluate R_T 21.16 min., at 103°, Argon flow-rate 45 ml./min.

Dimethyl sulphoxide as a solvent for base-catalysed aromatisation of diacetylenes.

Dimethyl sulphoxide (111) was dried before the reactions by distillation, drying over B.D.H. molecular sieve type 4A and redistillation.

On addition of potassium t-butoxide (1.5 g.) to a solution of hepta -1, 6-diyne (0.3 g.) in dimethyl sulphoxide (15 ml.), there was an immediate exothermic reaction with intense blue colouration which gradually darkened. The infrared spectra of the products (table 9, page 35) after reaction times of fifteen minutes and thirty-six hours at room temperature were substantially the same and contained no toluene aromatic absorption. The same product (110 mg.) was isolated from a similar reaction from which no aliquots were removed. The nature of the main product was not investigated further but is believed to be a vinyl thioether (117). Similar results were obtained in the analogous reaction of octa -1, 7-diyne, and again there was no trace of the expected aromatic isomers O-xylene and ethyl benzene.

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PART II

SECTIONS A and B

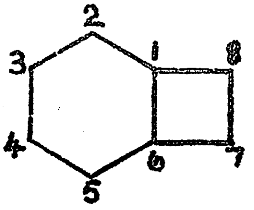
PREFACE

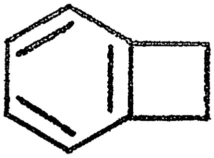
When the aromatisation work described in Part I of this thesis was nearing completion, and it became obvious that the reaction was general for the type of acetylenic groupings described therein, the question arose as to whether polybromides, as a source of potential acetylenes by elimination of hydrogen bromide, under the strongly basic conditions of the reaction, would aromatise. The readily available 1, 2, 5, 6 - tetrabromocyclooctane was chosen for study as loss of hydrogen bromide might result in either a highly strained cyclooctadiyne or, by ensuing rearrangement, benzocyclobutene. Dehydrobromination gave the latter system and cyclooctatetraene, as a reasonable intermediate was consequently isomerised to the same aromatic product. The mechanism involved in these two cases is possibly different and they will be dealt with separately in the following pages as sections A and B.

PART II

SECTION A

Rearrangements involving 1, 2, 5, 6 - tetrabromocyclooctane.





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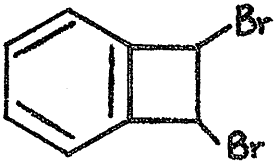

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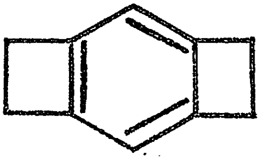

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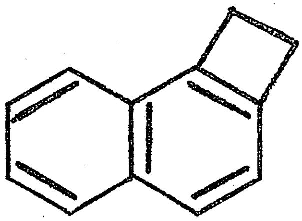

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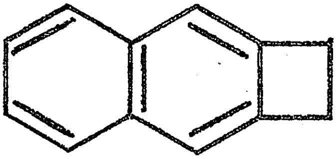

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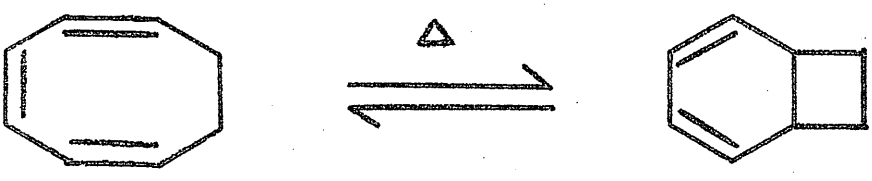

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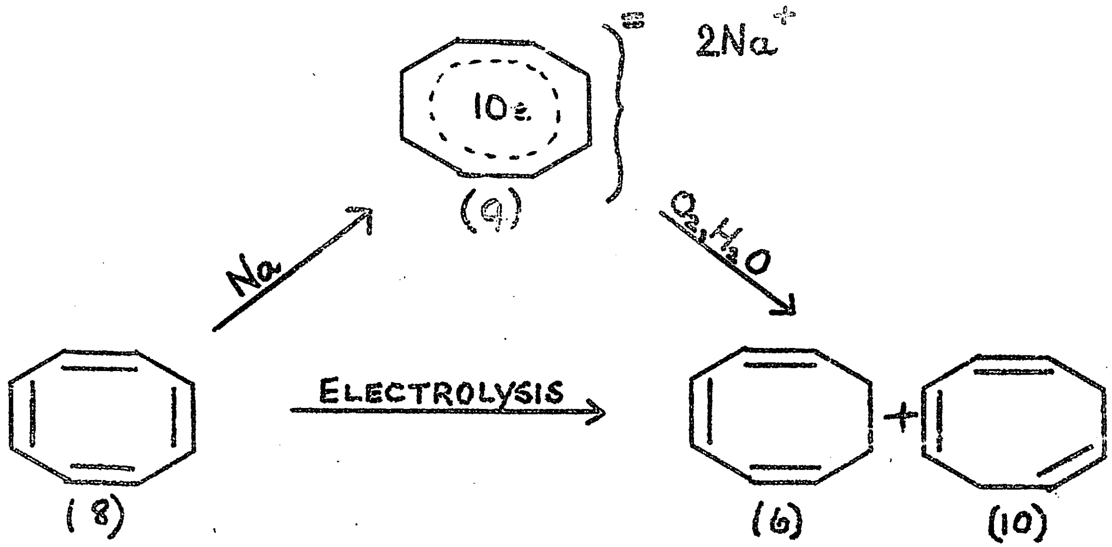
(7)

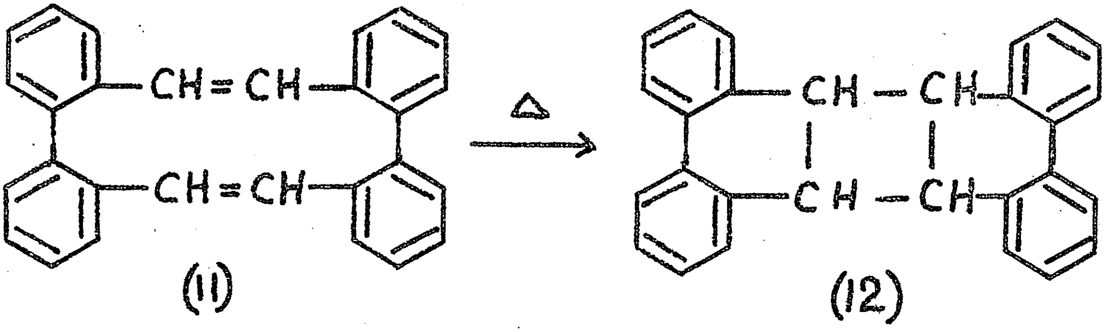
INTRODUCTION

Benzocyclobutene (1) was first mentioned in the literature by Perkin[1] in 1888 and the first attempted synthesis recorded by Willstätter[2] in 1907. It is now known that the first synthesis of a genuine benzocyclobutene derivative, 7, 8 - dibromocyclobutene (2), was achieved by Finkelstein[3] in 1910, but the uncertainty of this structure led to a lapse of interest in benzocyclobutenes until Cava[4] vindicated Finkelstein's claims and, further, prepared benzocyclobutene itself.[5] Interest then quickly revived and a large number of benzocyclobutene derivatives are now known. Benzocyclobutene has been prepared by four different routes[5,6,7,8] but the yields are small and no simple synthesis has yet been devised. Some higher homologues benzo [1, 2 : 4, 5] dicyclobutene (3),[9] naphtho [a] cyclobutene (4)[10] and naphtho [b] cyclobutene (5)[11] have also been prepared. Very able reviews on the chemistry of benzocyclobutenes have been compiled by Craig,[12] and Baker.[13,14]

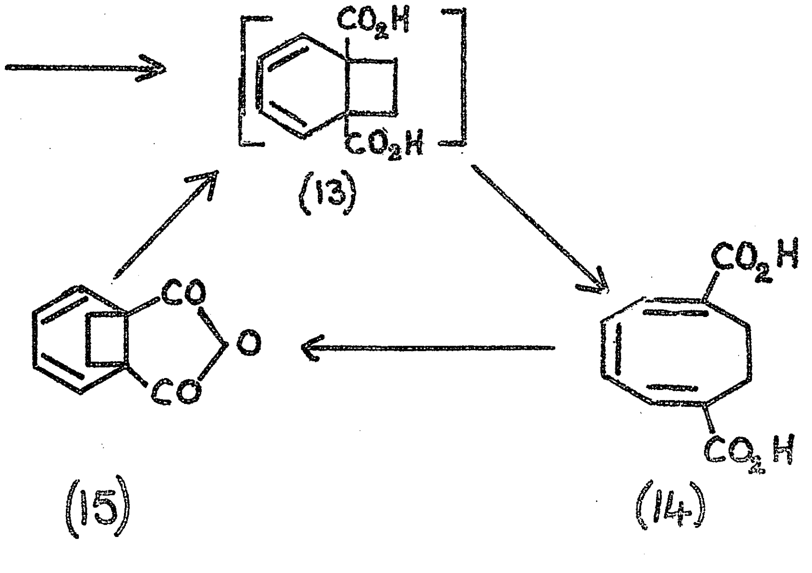
The circumstantial evidence provided by the well established valence tautomerism effect exhibited by the mobile 1, 3, 5 - cyclooctatriene system (6) gives reasonable grounds to hope that an eight-membered carbocyclic system containing



10e
=
2Na+
(9)
Na
O2, H2O
ELECTROLYSIS
+
(8)
(6)
(10)



CH=CH
CH=CH
Δ
CH — CH
CH — CH
(11)
(12)

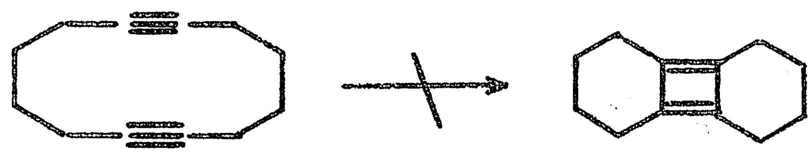


CO2H
CO2H
(13)
CO2H
CO2H
(14)
CO
O
CO
(15)

four double bond equivalents, which should be produced by dehydrobromination of 1, 2, 5, 6 - tetrabromocyclooctane, might aromatise readily to benzocyclobutene.

Reduction of cyclooctatetraene (8), best accomplished electrolytically[15] or by decomposition of its disodium salt (9)[16, 17] gives a mixture of 1, 3, 5 - cyclooctatriene (6) and 1, 3, 6 - cyclooctatriene (10), which can be completely converted to the conjugated system (6) by base treatment. When (6) is heated, an equilibrium mixture of 85% of (6) and 15% of the bridged structure bicyclo [4.2.0] octa -2, 4 - diene (7) is obtained.[18] The dynamic isomerism of (6) and (7) has been termed 'valence tautomerism' by Cope[18] and is an isomerism in which no atoms or groups are shifted. The only changes that occur are electronic displacements required to open or close the bridge of (7). A similar situation arises between 1, 2, 3, 4, 7, 8, 9, 10 - tetrabenzocyclododecahexaene (11) and bis-biphenylenecyclobutane (12).[19]

'Valence tautomerism' gives rise to complications in the preparation of 1, 6 - disubstituted bicyclo [4.2.0] octa -2, 4 - dienes. Thus Vogel et al,[20, 21] attempting to prepare the 1, 6 - dicarboxylic acid (13), found themselves with cycloocta - 1, 3, 5 - triene - 1, 6 - dicarboxylic acid (14) and had to go via the anhydride (15) to obtain the diacid (13).



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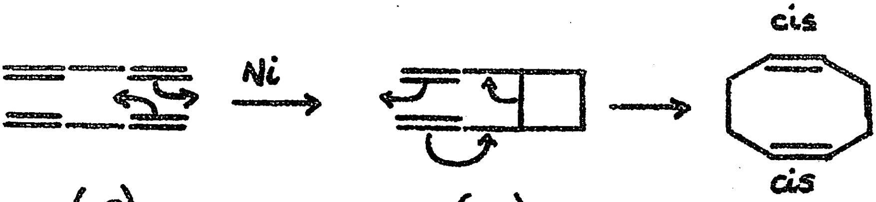
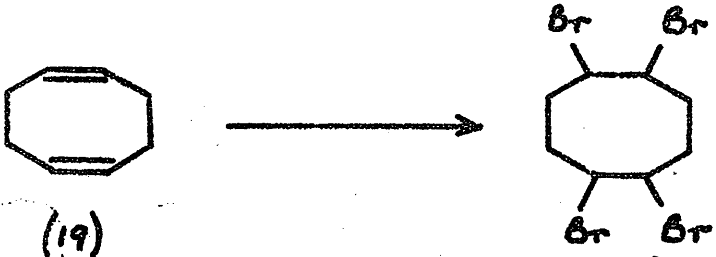
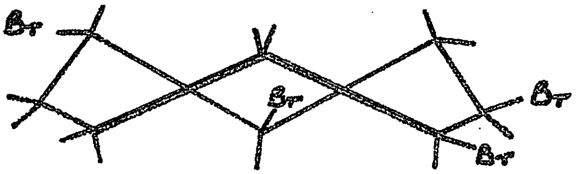


(18) (20) (19)



(19) (21)



(21 a)

It is worthy of note that Cram and Allinger,[22] using the above examples as analogies, unsuccessfully attempted to isomerise cyclododeca - 1, 7 - diyne (16) to the cyclobutadiene derivative (17). A further illustration of electronic rearrangements of this type is provided by the nickel catalysed dimerisation of butadiene (18) to cis, cis - 1, 5 - cyclooctadiene (19) which has been shown to involve cis - divinylcyclobutane (20) as an active intermediate.[23, 24]

The various cases presented above support the premise that an eight-membered carbon ring containing four double bond equivalents might aromatise by a similar mechanism; the equilibrium in this case would be expected to lie far to the aromatic side.

DISCUSSION

Bromination of cis, cis - 1, 5 - cyclooctadiene (19) with pyridinium bromide perbromide[25] gave colourless crystals of 1, 2, 5, 6 - tetrabromocyclooctane (21), m.p. 147 - 8°. Assuming trans addition of bromine, the most probable stereochemistry of this single substance is the trans-syn-trans configuration. The energy of conformational interconversion is very small in the cyclooctane series and the general broadening of peaks in the N.M.R. spectrum of this compound suggests a mixture of easily convertible conformations of which the 'crown' structure (21a) with all the bulky bromines pseudo-equatorial, is a likely one. The only other 1, 2, 5, 6 - tetrabromocyclooctanes reported in the literature were obtained independently by Willstätter [26] and by Jones [27] by bromine addition to the trans, trans - diene when isomeric mixtures of indefinite melting points were obtained. That sharp melting crystals were obtained from the cis, cis - diene probably indicates one isomer, and this would reflect the extent to which non-bonded interactions effect the steric course of bromine addition by pyridinium bromide perbromide.

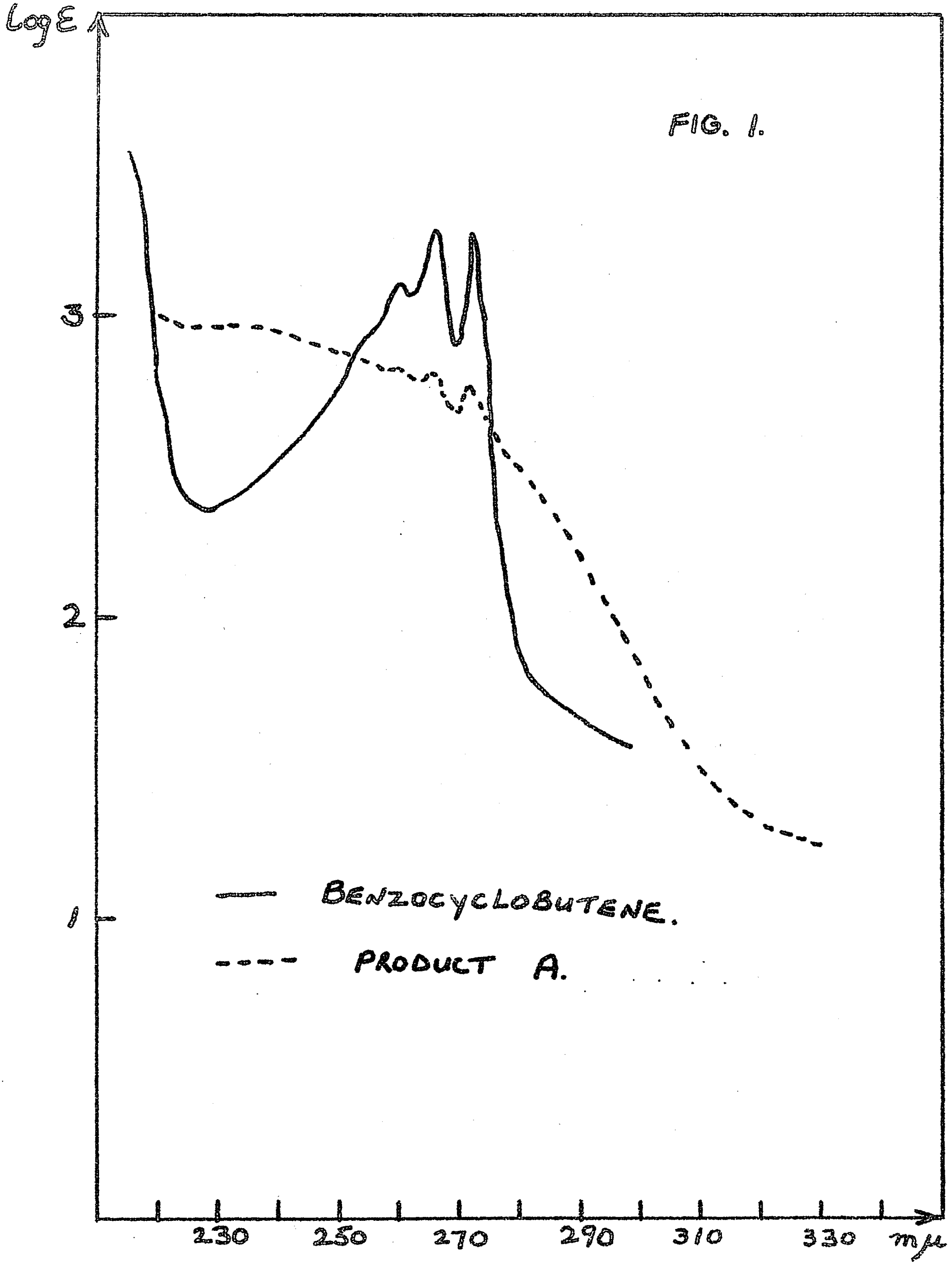

Log E
3
2
1
230
250
270
290
310
330
mμ
—— BENZOCYCLOBUTENE.
- - - - PRODUCT A.

FIG. 1.

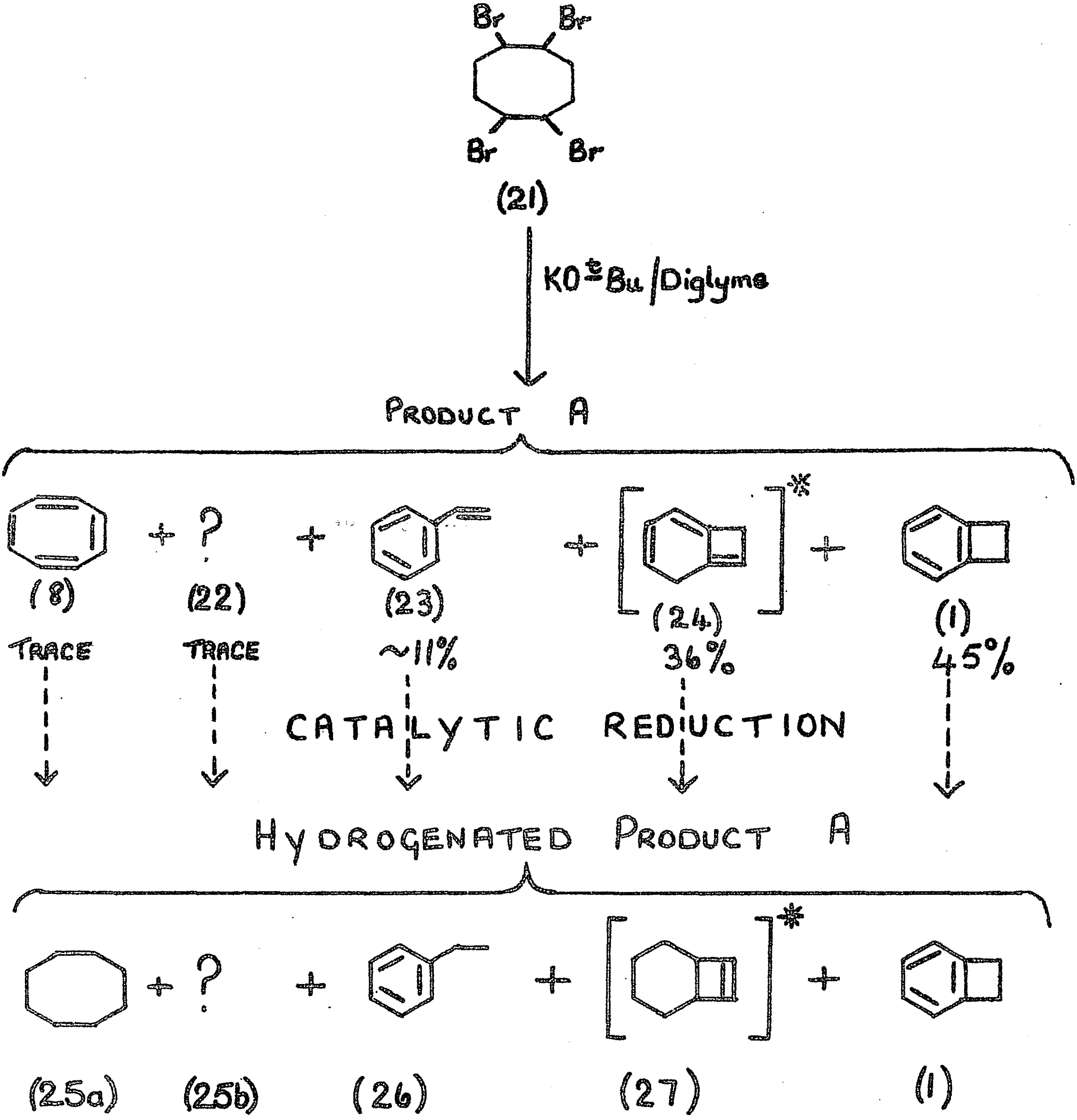
Dehydrobromination of 1, 2, 5, 6 - tetrabromocyclooctane (21)

The dehydrobromination of (21) was effected with a molar excess of potassium t - butoxide in diglyme at 120° for twenty-two hours, and the product was a bromine-free oil (product A). The infrared spectrum of this product was complicated, but prominent peaks which could be associated with olefinic (cis) bonds and with the o - disubstitution pattern (780 and 714 cm.$^{-1}$) exhibited by benzocyclobutene were present. The ultraviolet spectrum (fig. 1) showed broad absorption between 225 and 257 $m\mu$, then at longer wave lengths a pattern (260, 266 and 272 $m\mu$) indicative of benzocyclobutene[5] (fig. 1).

Yield of benzocyclobutene in product A.

Alkaline permanganate oxidation of product A gave phthalic acid, sublimed and identified as the anhydride. Comparison with the yield obtained from an identical oxidation of benzocyclobutene gave an estimated yield of 20% of benzocyclobutene from the tetrabromide. This agrees fairly well with the results obtained from the infrared analysis of product A, using the o - disubstitution band at 714 cm.$^{-1}$ (ε 240) which leads to an estimated yield of 23%.

FLOW SHEET 1



* POSTULATED STRUCTURE

G.L.C. analysis of product A (Flow Sheet 1)

The analytical G.L.C. investigations of product A showed that of the phases Apiezon 'L', squalane, silicone grease and silver nitrate/triethylene glycol, all supported on celite (table 2, runs 6, 7, 8 and 9), the first provided the best separation. Analyses with this column (table 1, run 1) demonstrated that product A contained at least four components, two of which were identified, by mixed chromatograms (table 2, runs 14, 15), as cyclooctatetraene (8) and styrene (23), present as trace and *ca.* 11%, respectively. The last and dominant peak, as more than 80% of the mixture, had the same retention time as benzocyclobutene (1), while the remaining unknown component (22) was present in trace quantity only. Analysis on the silver nitrate column gave the very interesting result that all but the last peak were completely retained under these conditions, and the sample size used indicated that this peak was diminished by more than half. Unsaturated molecules, especially those which form silver nitrate complexes e.g. cyclooctatetraene and cyclooctatrienes,[18, 27] are readily separable on silver nitrate columns.[28, 29] Retention of cyclooctatetraene and styrene was therefore not unexpected, but retention of more than half the last peak must mean that this peak, of the same retention time as benzocyclobutene (1), contains an unsaturated component (24) and a component,

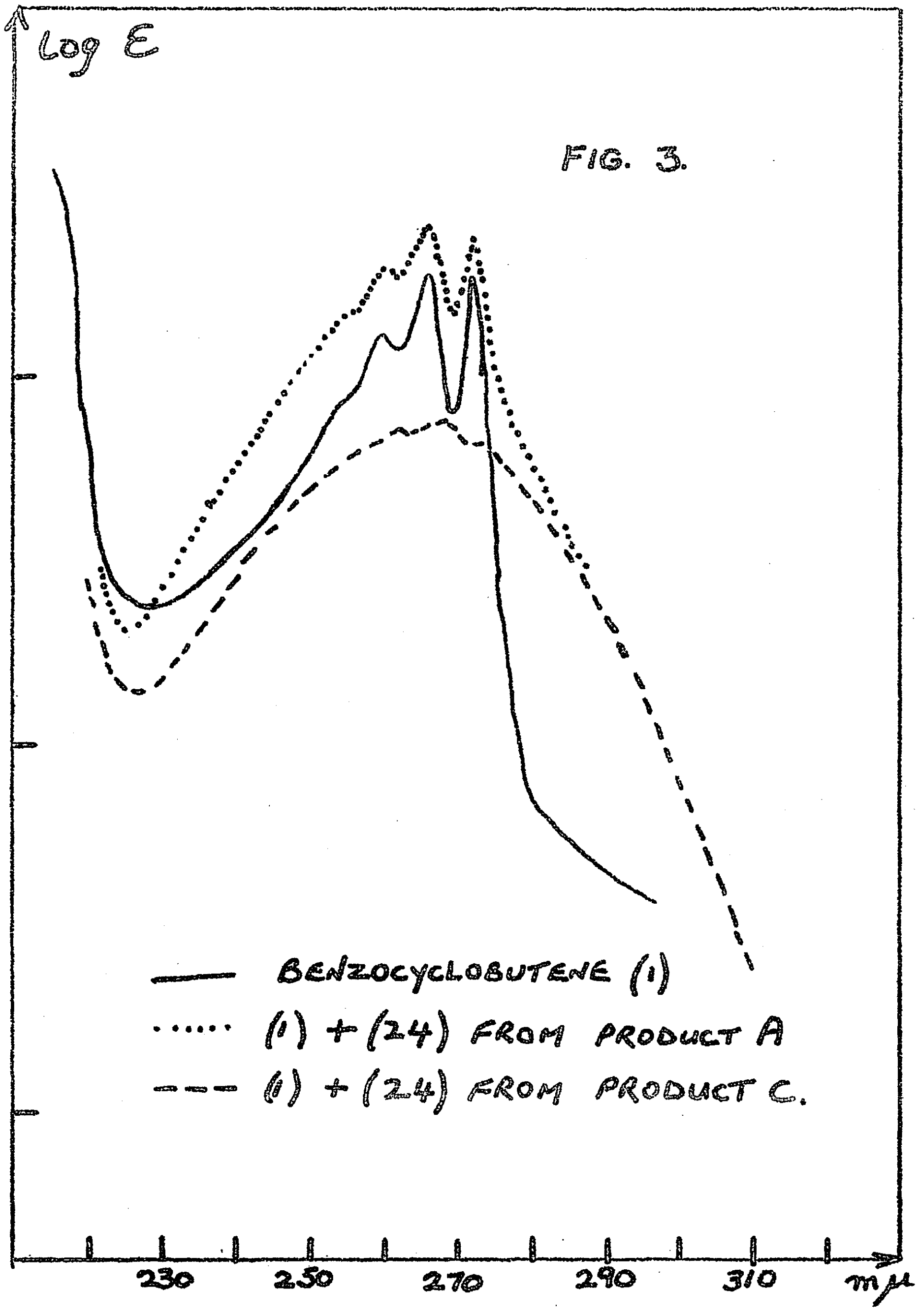


FIG. 3.

Log E
3
2
1
230
250
270
290
310
mμ
BENZOCYCLOBUTENE (1)
(1) + (24) FROM PRODUCT A
(1) + (24) FROM PRODUCT C.

presumably (1), which is not retained. Similarly, retention of the unknown (22) points again to unsaturation, and its retention time (table 1, run 1) suggests a close relationship with cyclooctatetraene.

The last peak was collected by preparative G.L.C. using a 1% silicone grease column. Its ultraviolet spectrum (fig. 3) was identical both in peak position and shape to that of benzocyclobutene.[5] The ε values were, however, lower presumably due to the presence of a little moisture in the collected fraction (see part I). The ultraviolet spectrum of unknown (24) must therefore be very similar to that of benzocyclobutene. The mass spectrum of the collected fraction had a cracking pattern identical to that of benzocyclobutene and cyclooctatetraene.[30]

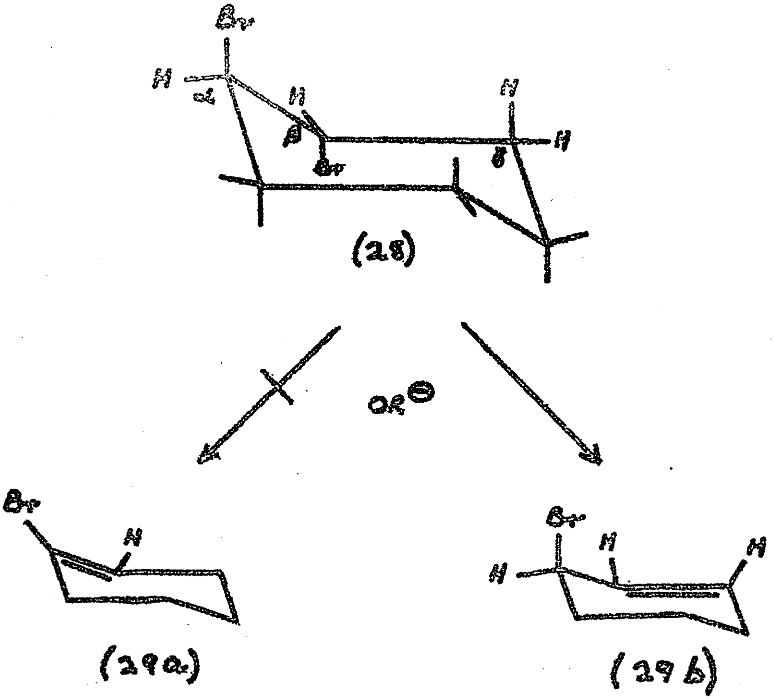
Complete hydrogenation of product A.

The oil resulting from the complete hydrogenation of product A showed infrared bands in the γ - CH region corresponding to those of ethyl benzene (696, 744 $cm.^{-1}$) and of benzocyclobutene (714, 780 $cm.^{-1}$) together with an additional peak at 698 $cm.^{-1}$. The peaks in product A at 808, 800, 775, 735, 700 and 672 $cm.^{-1}$ were now absent. Because cyclooctatetraene, styrene, and unknown (24) were present in unknown amounts in product A, no correlation of hydrogen uptake could be made to the structure of unknown (24). The presence of a peak at 698 cm.$^{-1}$ in the hydrogenated product suggests that hydrogenation of the unknown (24) has not gone to completion and that a cis-double bond remains. The ultraviolet spectrum of the reduced material was, as expected, identical to that of benzocyclobutene.

Analytical G.L.C. of hydrogenated product A.

(table 3, run 20) showed peaks which on the basis of mixed chromatograms (table 3, runs 21, 22, 24, 26) were assigned to ethyl benzene (26), unknown (25b) from unknown (22), unknown (27) (ca. 58% of mixture) and benzocyclobutene (1). Preparative scale G.L.C. on the Griffin and George apparatus using a 10% Apiezon 'L' column was only partially successful in that only ethyl benzene was effectively removed. The infrared spectrum of the resultant oil showed peaks at 1660 and 698 cm.$^{-1}$ attributed to a cis - double bond, and since the only component present in an amount sufficient to give such absorption is unknown (27), this apparently contains a cis-double bond formed in such a position from unknown (24) that it is immune to further reduction under these conditions.

To derive some idea of the types of structures which might be encountered together with benzocyclobutene, the mechanism of dehydrobromination will now be considered.



(28)

(29a)

(29b)

The mechanism of dehydrobromination.

The mechanism for bimolecular 1,2-elimination requires: (a) that the departing nucleophile (in this case $Br.^{\ominus}$) be as far removed as possible from the proton under extraction by the base, and, (b) that this proton, the α- and β- carbons and the departing halogen be coplanar. In cyclic systems this happy situation is achieved when the substituents are *trans*-diaxial. However, *trans*-addition of bromine to a *cis*-cycloalkene leads to a situation in which the α- hydrogen and the β-bromine will be mutually *cis* and cannot normally attain the *trans*-diaxial position e.g. (28) on the opposite page. α, β- Elimination producing a vinylic bromide (29a) will not therefore be favoured, and β, γ- elimination to give an allylic bromide (29b) will be preferred. This is the case in the cyclohexane series illustrated (28), but in the very much more flexible cyclooctane series both α, β- and β, γ- elimination must be considered. In the proposed 'crown' conformation the bromines probably occupy the equatorial positions in a *trans* - *syn* - *trans* configuration. Consider the two cases:

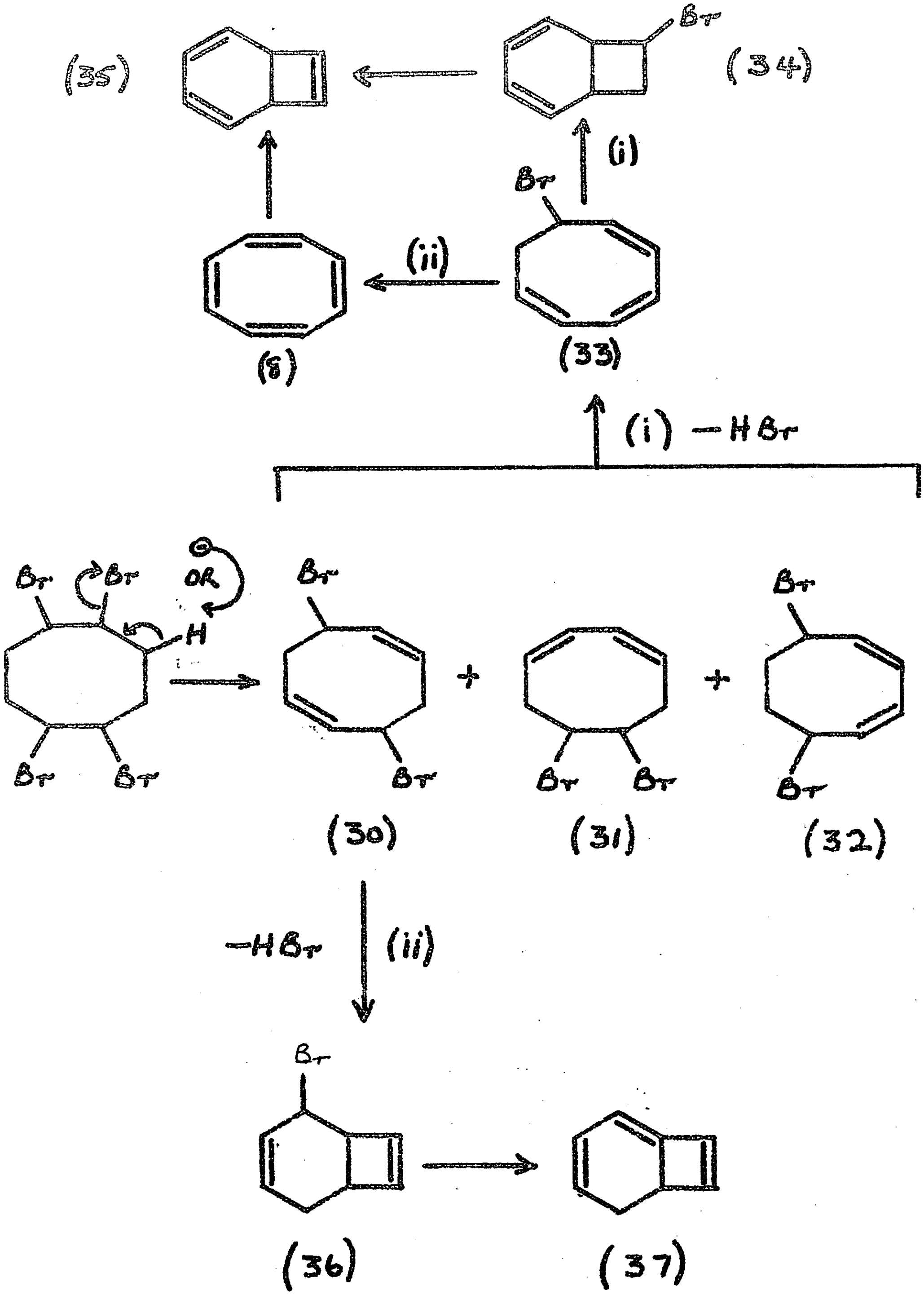
A β, γ- Elimination of two moles of hydrogen bromide.

B α, β- Elimination of two moles of hydrogen bromide.

Case A. Initial loss of two moles of hydrogen bromide by β, γ- elimination could give the structures (30, 31 and 32).

DEHYDROBROMINATION OF 1,2,5,6-TETRABROMOCYCLOOCTANE

CASE A.



(a) Further β, γ - elimination could then give an intermediate 8 - bromocycloocta -1, 3, 5 - triene (33) which could then either (i) undergo valence tautomerism to give 7 - bromobicyclo [4.2.0] octa -2, 4 - diene (34) followed by elimination of the last mole of hydrogen bromide to give bicyclo [4.2.0] octa -2, 4, 7 - triene (35), or

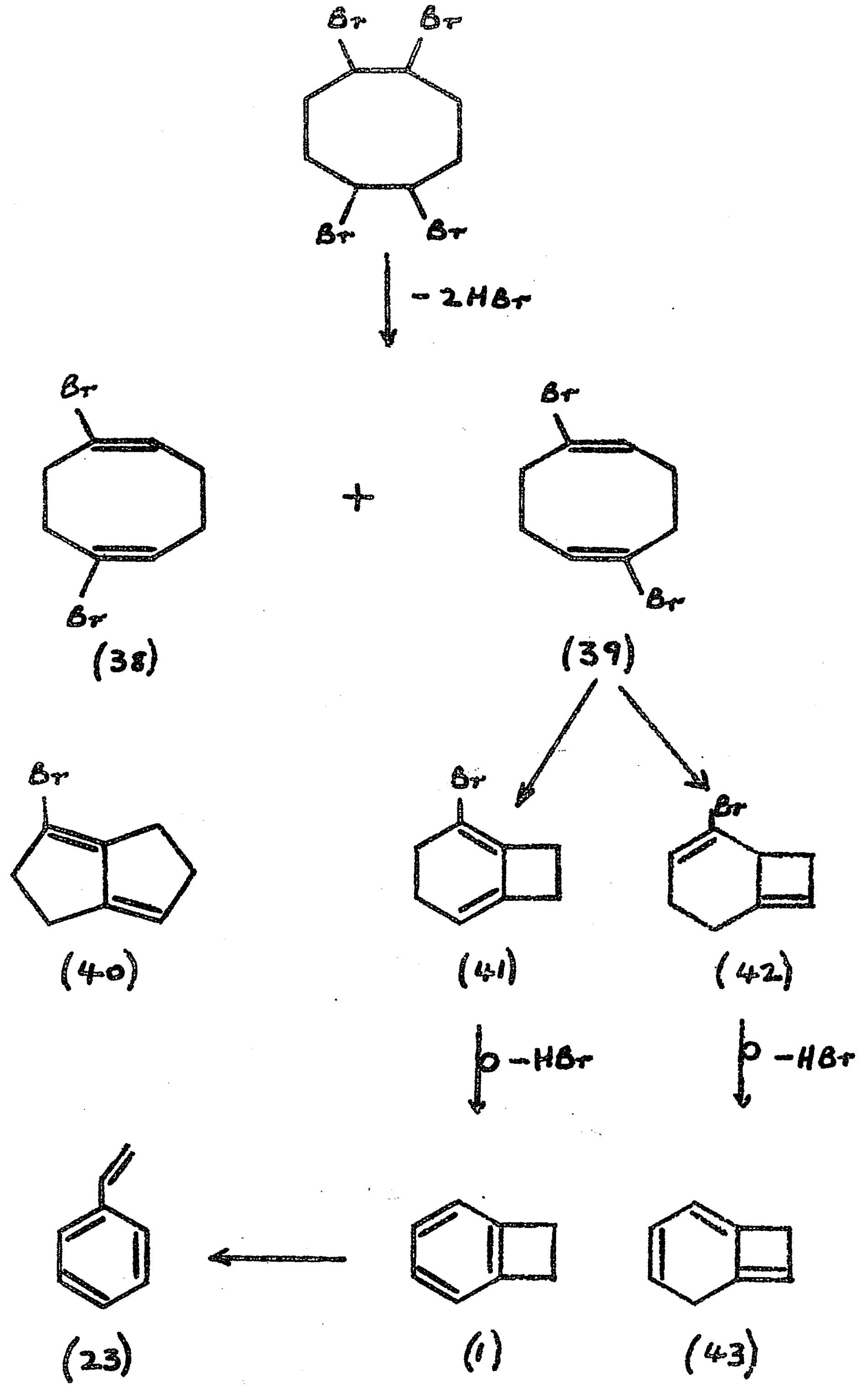
(ii) successively lose hydrogen bromide giving cyclooctatetraene (8) followed by tautomerism to (35) (See later). Both these pathways are possible. Tautomerism of the bicyclo [4.2.0] octatriene system has been dealt with earlier in the introduction, while Reppe[40] and others have shown that cyclooctatetraene often reacts as (35).

(b) 1, 4 - Transannular loss of hydrogen bromide from (30) would give 2 - bromobicyclo [4.2.0] octa -3, 7 - diene (36). (The hydrocarbon bicyclo [4.2.0] octa -3, 7 - diene was prepared by Ziegler[31] by sodium reduction of cyclooctatetraene. The hydrocarbon is stable to further reduction by this method). Further loss of hydrogen bromide would then give bicyclo [4.2.0] octa -1, 3, 7 - triene (37). Both mono - and dimethylene cyclobutenes are known,[32, 33] and (37) is therefore a feasible structure.

1, 3 - Transannular elimination from either (31) or (32) and further dehydrobromination would lead to a cyclopropene or methylene cyclopropane which is sterically unlikely.

DEHYDROBROMINATION OF 1,2,5,6-TETRABROMOCYCLOOCTANE

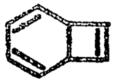
CASE B:



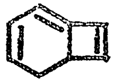
Case B. Initial loss of two moles of hydrogen bromide by α, β - elimination would give structures (38) and (39). The 1 - and 5 - positions are so far apart in the cycloocta - 1, 5 - diene ring that transannular elimination across these positions, to give the [3.3.0] bicycle (40), is unlikely to occur. 1, 4 - Elimination is much more probable and would give 2 - bromobicyclo [4.2.0] octa -1, 5 - diene (41) and 2 - bromobicyclo [4.2.0] octa -2, 6 - diene (42). Dimethylene cyclobutane is known [34, 35] and structure (41) although strained is not unreasonable. Dehydrobromination and rearrangement would then give benzocyclobutene (1) which might rearrange further to styrene (23). Structure (42) could similarly give bicyclo [4.2.0] octa -1, 3, 6 - triene (43).

Any isomers of the bicyclo [4.2.0] octatriene system which have not been shown to arise in cases A and B, can be formed readily by base-catalysed prototropic rearrangement of those illustrated.

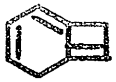
Possible structures for unknown (24) are (35, 37, 43, 44, 45). Shozda[36] has proposed the bicyclo [4.2.0] octa - 2, 4, 6 - triene (47) as intermediate in the preparation of 7, 7, 8 - trifluorobenzocyclobutene (48) by dehydrohalogenation of (46). He suggests that, by analogy to the slow isomerisation of methylene cyclohexa - 2, 4 - diene (49) to toluene at room temperature,[37] the proposed intermediate (47) would be expected



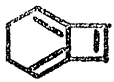
(35)



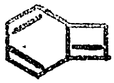
(37)



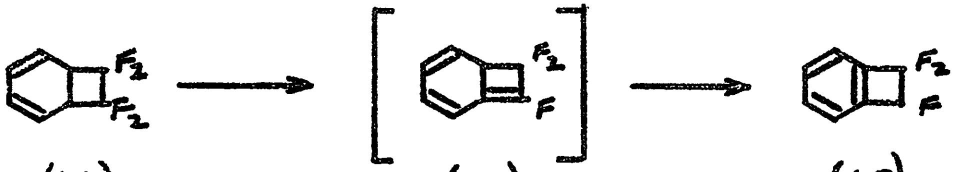
(43)



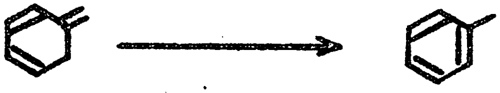
(44)



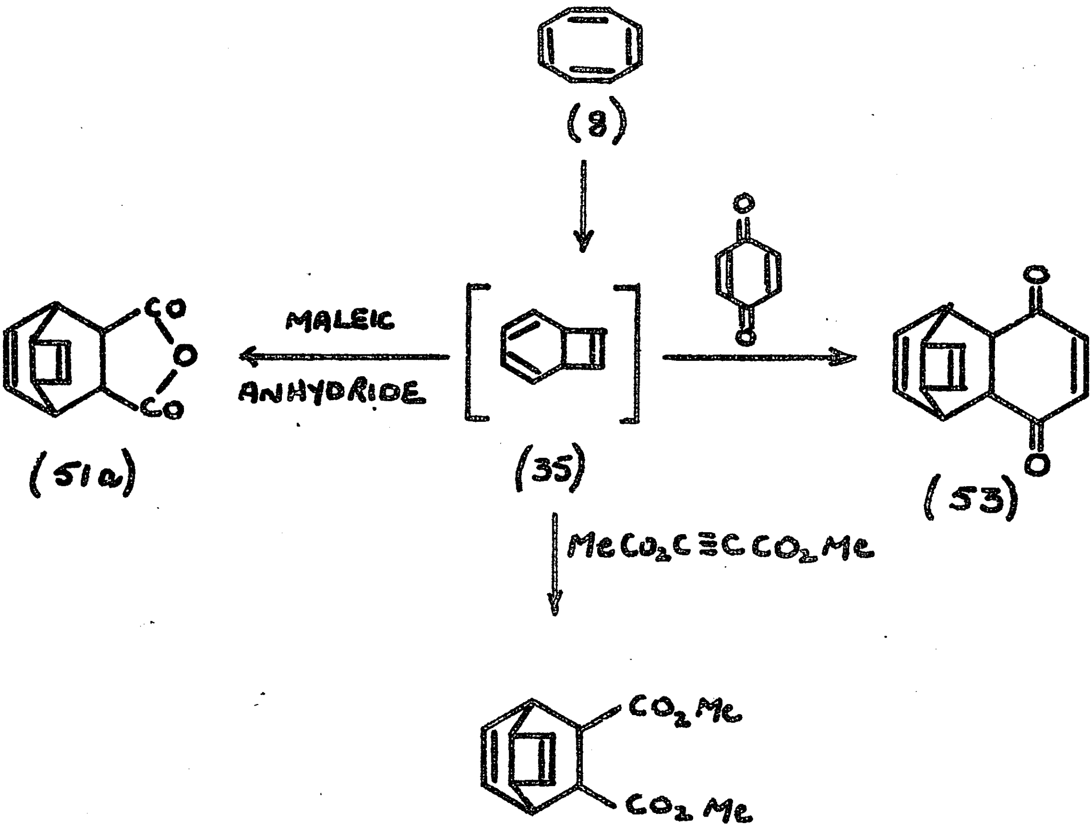
(45)



(46) (47) (48)



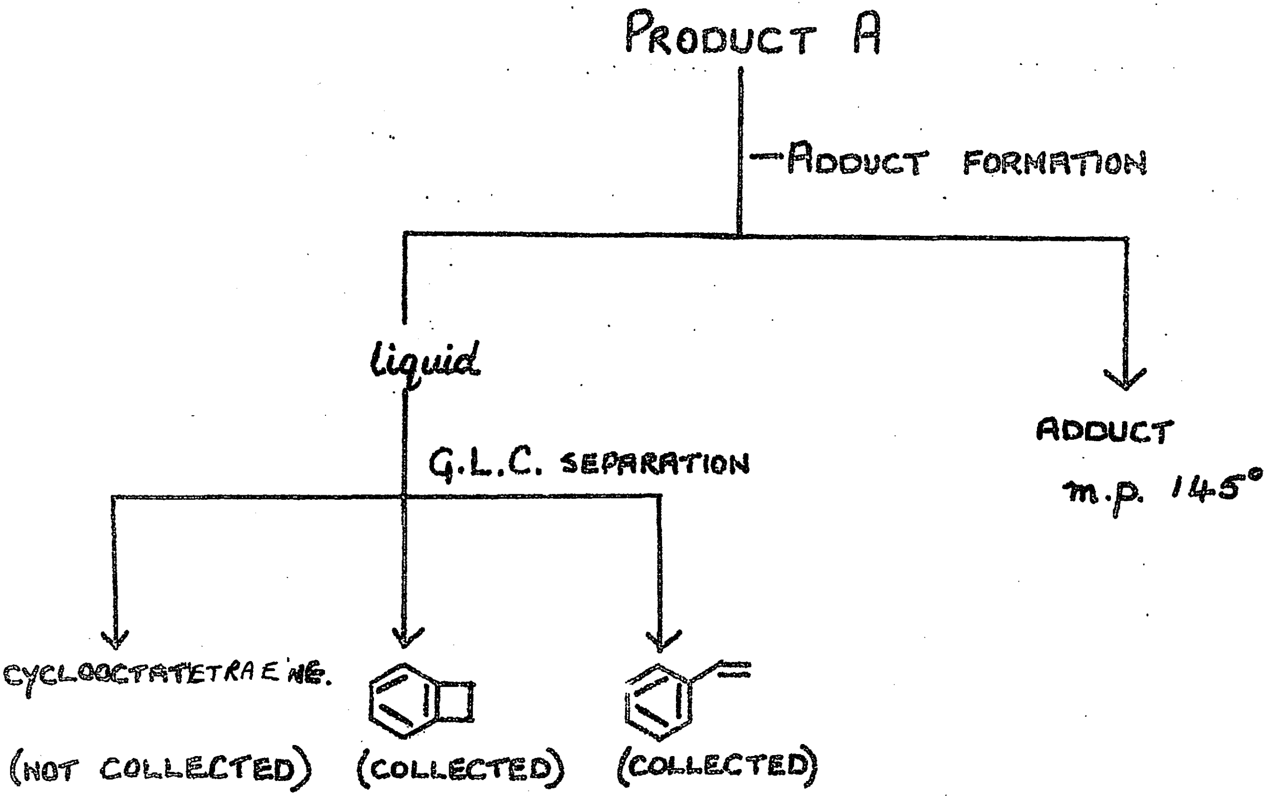
(49) (50)

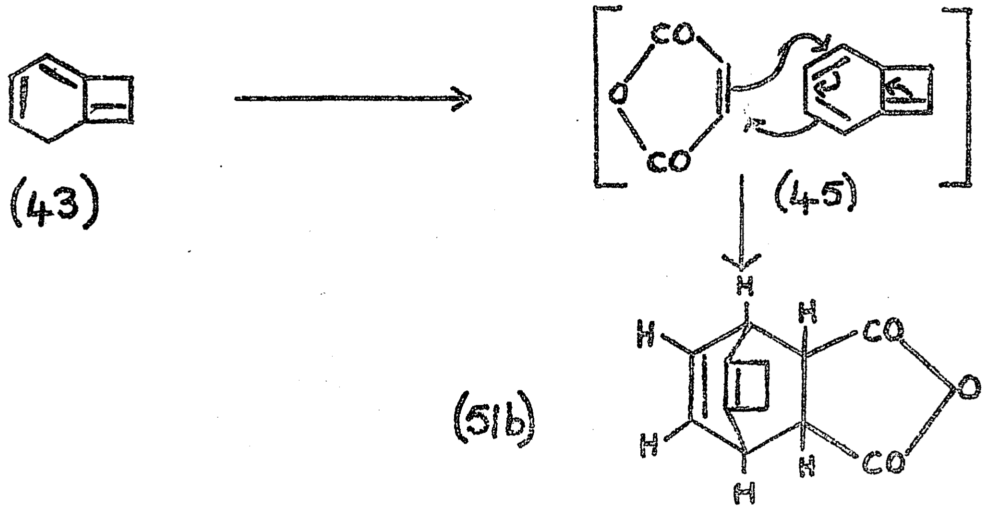


(52)

FLOW SHEET 2

SEPARATION OF PRODUCT A BY ADDUCT FORMATION.





aromatise to the product (48). Although the Δ^6 - double bonds in structures (47) and (45) are in quite different electronic environments, it is believed that this latter structure would also readily aromatise, and is therefore an unlikely candidate for the unknown structure (24).

Diels - Alder adduct formation of product A and the isolation of benzocyclobutene. (flow sheet 2)

Reppe et al.,[40] in their excellent war-time researches on cyclooctatetraene, showed that cyclooctatetraene forms adducts corresponding to dienophilic addition to its valence tautomer (35). Thus with maleic anhydride cyclooctatetraene gives (51a),[18, 40] with dimethyl acetylene dicarboxylate (52)[41] and with benzoquinone (53)[42] and the structures established by Friess,[43] Cope,[18] Avram[41] and Cookson.[44] Maleic anhydride adduct formation seemed a very plausible method of removing unknown (24) from product A as a derivative which would directly reflect the unknown structure.

The schematic separation of product A by adduct formation is shown in flow sheet 2. Treatment of product A with maleic anhydride in refluxing benzene for two hours yielded on adduct, m.p. 145°, and an oil. Analytical G.L.C. (table 1, run 2) showed a proportional decrease of the area of the last peak with respect to the others, demonstrating the absence of (24).

FIG. 2

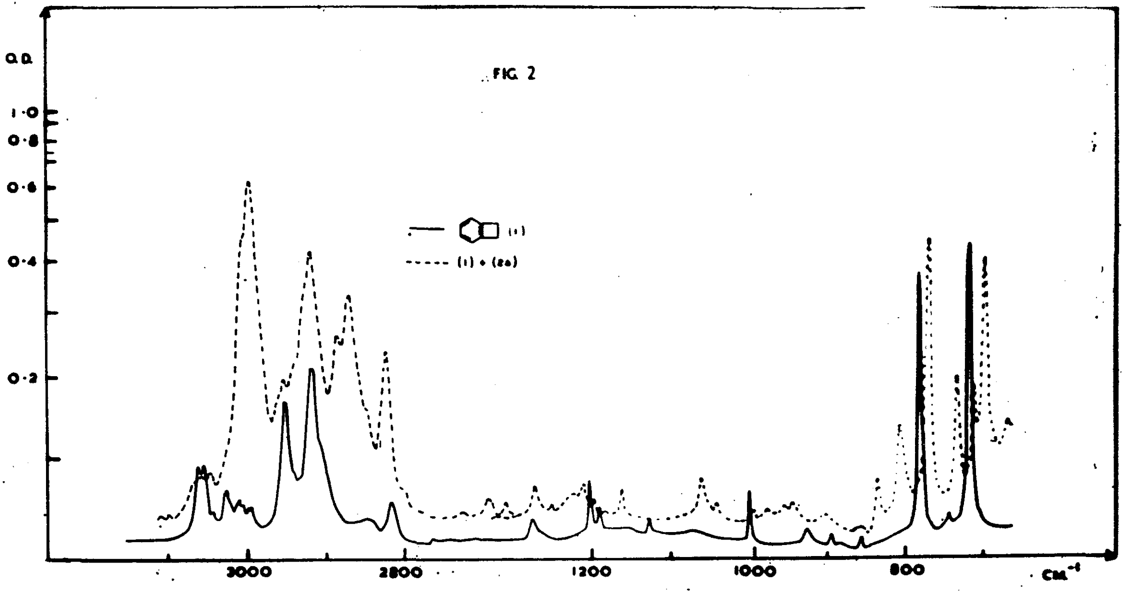


Table 4.

Infrared spectral data of unknown (24) by subtracting the above curves.

Frequency (cm.$^{-1}$)	Assignment
3006	CH stretch, trisubstituted double bond
3000	CH stretch, trisubstituted double bond
2970	CH stretch, CH_2
2920	CH stretch, CH_2
840	γ - CH, trisubstituted double bond.
810	γ - CH, trisubstituted double bond
774, 736	γ - CH, ring substitution
700	γ - CH, *cis*. C = C.

The peaks corresponding to (23) and (1) were collected by preparative G.L.C. and their infrared spectra found to be identical to those of styrene and benzocyclobutene respectively. This constitutes a new synthesis of benzocyclobutene.

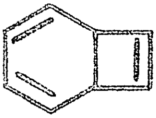
The structure of unknown (24)

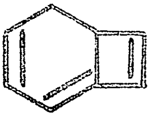
Unknown (24) was also encountered in the aromatisation of cyclooctatetraene and its presence confirmed by G.L.C. analyses before (table 2, run 19) and after hydrogenation to (27) (table 3, runs 20, 23). The physical and chemical evidence, from which a tentative structure for (24) is derived, is taken from both these sources and discussed below.

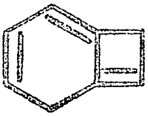
(i) Infrared spectral data. During the course of investigations into the aromatic product obtained from cyclooctatetraene, the G.L.C. peak, corresponding to the isomeric mixture containing both benzocyclobutene (1) and (24), was collected. The accurate infrared spectra of this fraction and of benzocyclobutene were determined and are shown in fig. 2. By subtraction a spectrum of (24) was obtained and the absorption bands in this, together with their assignment, are listed in table 4. If these assignments are correct, unknown (24) contains one *cis* and two trisubstituted double bonds. Of the possible structures (35, 37, 43, 44 and 45) in the bicyclo [4.2.0] octatriene series, only (43) and (44) agree with this spectrum.

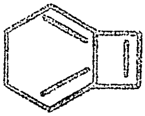
TABLE 5.

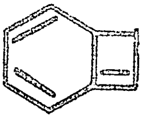
POSSIBLE STUCTURES FOR UNKNOWN (24).


(35)

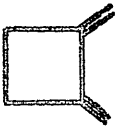
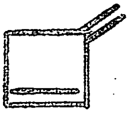
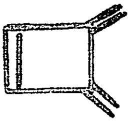
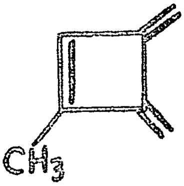
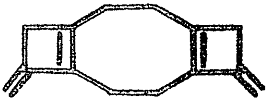
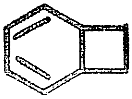

(37)


(43)


(44)


(45)

ULTRAVIOLET CHARACTERISTICS OF RELATED COMPOUNDS.

STRUCTURE	λ_{max}	$\log \varepsilon$	REFERENCE
 (54)	237 246 255	3·99 4·01 3·81	34, 35.
 (55)	221	4·57	32, 39.
 (56)	211 248	5·0 4·3	33.
 (57)	210 245	4·50 3·76	38.
 (58)	225	5·43	38.
 (59)	274	3·52	18.

(ii) Ultraviolet spectral data. The ultraviolet spectra of mixtures containing only benzocyclobutene and unknown (24) derived by G.L.C. separation of the last peak in (a) product A, and (b) isomerisation product C from cyclooctatetraene, together with that of authentic benzocyclobutene, are shown in fig. 3. It is difficult to deduce a spectrum for unknown (24) from these, but it appears to have general broad absorption between 250 - 280 mμ .

The ultraviolet characteristics of related types of compounds are shown in table 5. From these, the surprising feature arises that the absorption of conjugated exomethylenes is only slightly effected by a double bond in the cyclobutane ring, e.g. (54), (56) and (57) all absorb at ca. 246 mμ . This suggests that (56) and its 3 - methyl homologue are not conjugated trienes, but dienes cross-conjugated with a double bond. Similarly, (55) and (58) do not behave as conjugated dienes.

Although structure (44) does not strictly contain exomethylenes the above considerations eliminate it as a possible structure for (24). Any of the other possible structures (35, 37, 43, 45) would be more in harmony with the deduced ultraviolet spectrum.

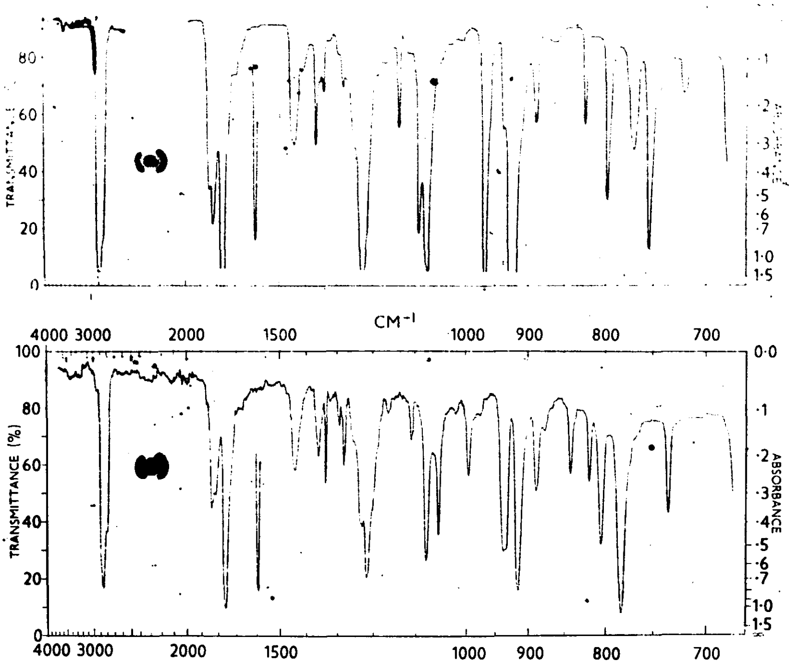


FIG. 4

(a) MALEIC ANHYDRIDE ADDUCT OF PRODUCT 'A'

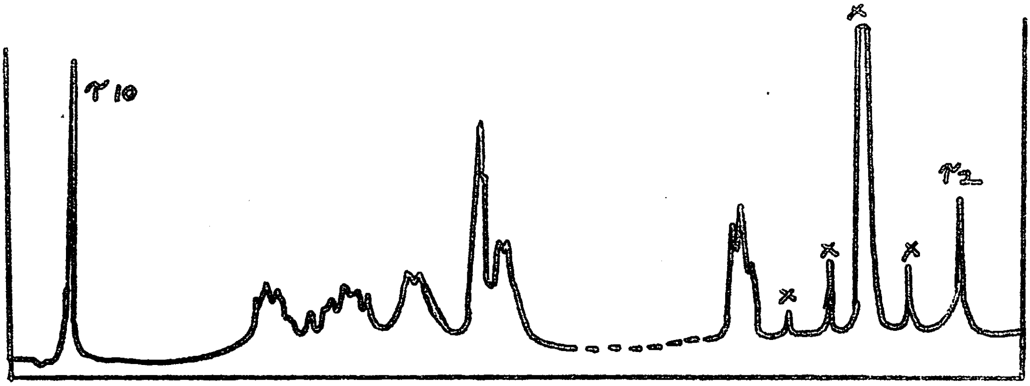
(b) " " " " C.O.T.

Table 6.

Group frequencies coincident in the above spectra.

Frequency (cm.$^{-1}$)	Assignment
1843 - 1760	3 peaks; C=O vibs; cyclic anhydride
1250 - 1220	C - O vibs.
1100 - 1050	2 peaks; - CH vibs. (substituted cyclohexane type ?).
970 - 870	4 peaks, - CH, substituted cyclobutane type.
840 - 720	5 peaks, substituted cycloalkene
680 - 720	γ- CH, *cis*. C = C.

FIG. 5



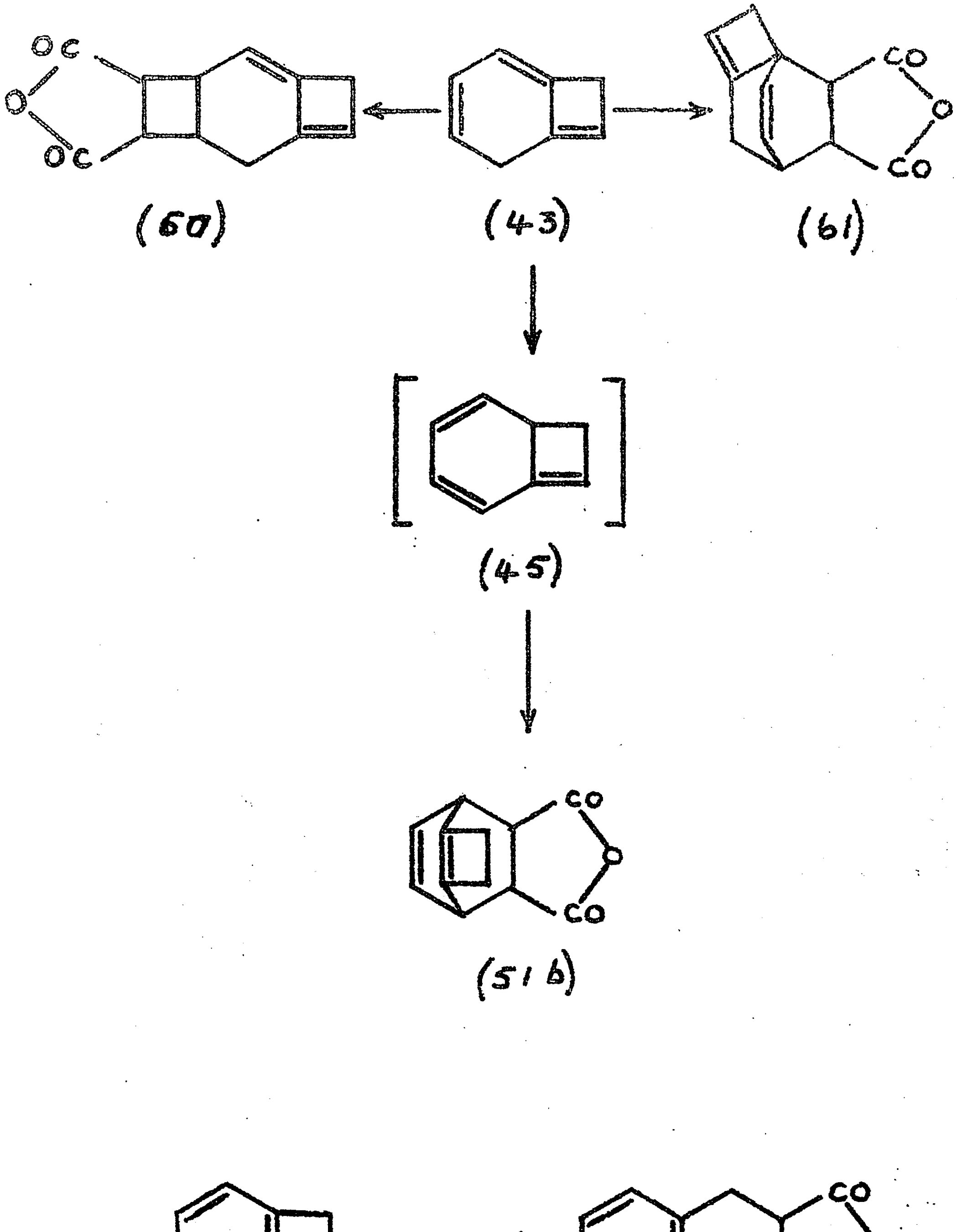
N.M.R. SPECTRUM OF THE MALEIC ANHYDRIDE ADDUCT OF PRODUCT A IN CHLOROFORM (1M. SOLUTION)

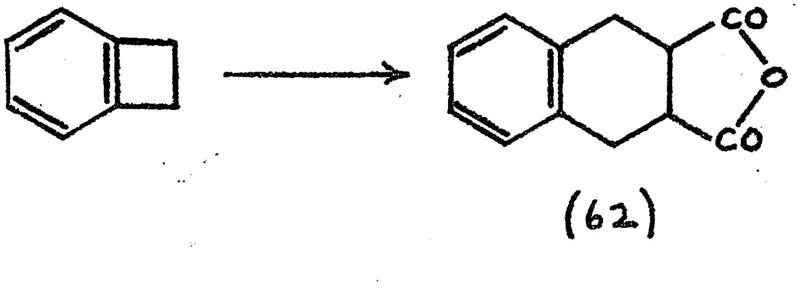
X = $CHCl_3$

(iii) <u>The Diels - Alder adduct of (24)</u>. The adduct, m.p. 145°, had a mass-spectrometric molecular weight of 202 ($C_{12} H_{10} O_3$) and was not identical to the corresponding adducts of cyclooctatetraene (51a), or benzocyclobutene (62)[45, 46] melting points, 168 and 186-7°, respectively. The adduct of cyclooctatetraene was prepared both by the method of Reppe[40] and by the method already described for product A. In the latter case the yield was very much smaller which is reflected by the presence of cyclooctatetraene in product A, after adduct formation.

The infrared spectra of the adducts from cyclooctatetraene and product A, shown in fig. 4, were not identical, but very similar and had the group frequencies, listed in table 6, in common. The structures of the two adducts would therefore appear to be very similar and further, a mixture of the two melted at 144°, i.e. almost no depression from the adduct of A. Without additional evidence structure (35) would be assigned to the unknown (24), discrepancies in melting point and infrared spectra of the adducts being accounted for by different stereochemical configurations.

The N.M.R. spectra of the two adducts, however, differed not only in the peak positions, but also in the areal distribution of these peaks. Thus while the N.M.R. of the cyclooctatetraene adduct agrees with the structure (51a)

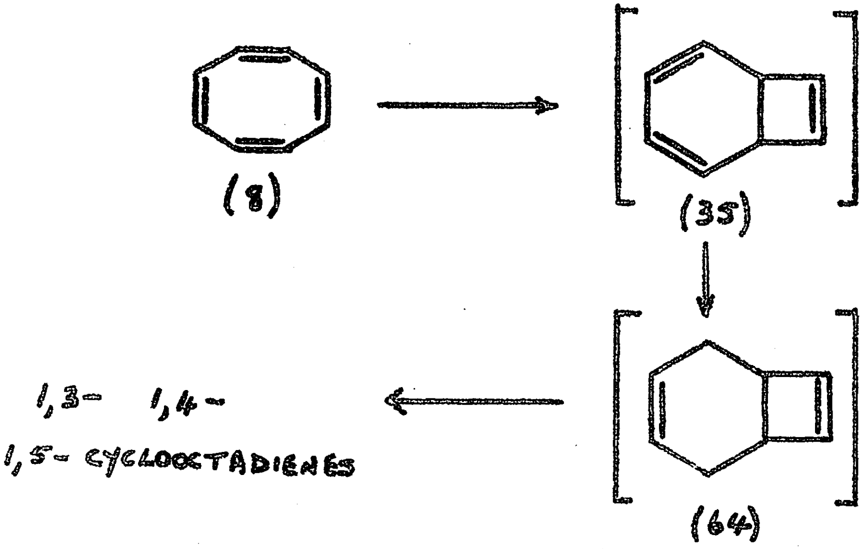

OC
O
OC
CO
O
CO
(60)
(43)
(61)
(45)
CO
O
CO
(51 b)


CO
O
CO
(62)

(the area ratio corresponding to olefinic and methine protons being as expected 2 : 3; methylenic protons absent) that of the unknown adduct (fig. 5) does not. In this case the peaks corresponding to olefinic (τ 3.5 - 3.6) and methine protons (τ 7.2 - 7.4) are in the areal ratio of 1 : 2. There are also signals assigned to methylenic protons (τ 8 - 8.6). Structure (35) can therefore be discounted for unknown (24).

Of the possible structures, only (43) has not been eliminated. Normal 1, 4 - addition of maleic anhydride would give structure (61) which would not agree with the N.M.R. It is difficult to envisage 1, 2 - addition to give (60) and, in any case, the infrared spectrum of this would not resemble that of the cyclooctatetraene adduct so closely. The most likely structure for the unknown adduct is (51b) which could conceivably arise by 1, 4 - addition of maleic anhydride to the valence tautomer (45) of (43) with concurrent migration of the cyclobutene double bond from the 6, 7 to the 1, 6 - position.

Valid criticisms can obviously be made about the suggested route from (43) to (51b) but the most serious argument against structure (43) stems from hydrogenation work. The isomerisation product of cyclooctatetraene (see section B), proved to contain (24), was completely hydrogenated with palladium on charcoal and the component (27), corresponding to hydrogenated (24) was collected by preparative G.L.C. The salient absorption bands


(8)
(35)
(64)
1,3- 1,4-
1,5- CYCLOOCTADIENES

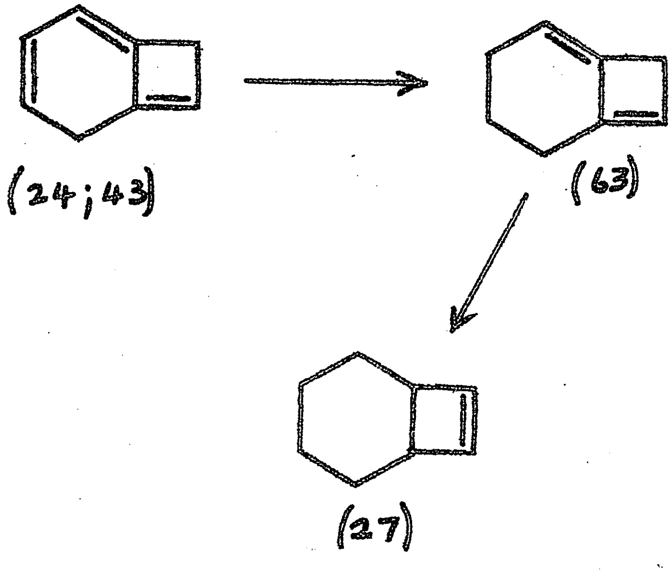
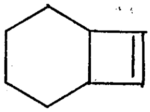

(24;43)
(63)
(27)

Table 7.

The infrared spectral data of component (27) and ethyl cyclohexane.

Frequency (cm.$^{-1}$)		Assignment.
Ethyl cyclohexane	(27)	
	3010	cis $C = C$
	2900	$- CH_2 -$
	2680	cyclohexane ring
987	980	cyclohexane ring
889	892	
754	751	
	702	cis $C = C$

Possible structure for (27) is 

in the accurate infrared spectrum of this component and their assignment are listed in table 7 with those of ethyl cyclohexane. The spectrum of (27) is in agreement with the structure of bicyclo [4. 2. 0] oct - 7 - ene, i.e. a substituted cyclohexane with a *cis* - double bond outside the six-membered ring. A reasonable pathway to this is initial 3, 4 - addition of hydrogen to bicyclo [4. 2. 0] octa - 1, 3, 6 - triene (24; 43) giving the 1, 6 - diene (63) followed by rearrangement, as shown, to (27). The weak point in this argument for structure (27), and therefore for (43), is this cessation of hydrogenation at (27) under conditions which would be expected to reduce a *cis* - double bond.

Jones,[27] during an examination of the reduction of cyclooctatetraene by sodium in boiling alcohols, discovered that all three cyclooctadienes were formed. The presence of 1, 3 - octadiene was unexpected as sodium in alcohols generally reduces conjugated double bonds leaving isolated double bonds untouched. To explain the formation of all three isomers he suggested initial isomerisation to bicyclo [4. 2. 0] octa - 2, 4, 7 - triene (35), then 1, 4 - addition of hydrogen giving the 3, 7 - diene (64). Further hydrogenation and ring opening of this would give all three isomeric cyclooctadienes.

The processes involved in hydrogenation over palladium on charcoal and with sodium in alcohol are different and no analogies can be taken from the work by Jones. It does show, however, that anomalies have been encountered in the hydrogenation of cyclooctatetraene and its tautomeric bicyclo [4, 2. 0] octatriene system.

Mass spectometry is not really adaptable to systems such as (51a) and (51b) because these so readily undergo electronic rearrangements, when subjected to the large energy imput, that the resulting cracking pattern is very difficult to interpret in terms of the original structure. The unknown adduct on mass spectroscopic examination readily loses stable fragments corresponding to $C_2 H_2$ and $C_4 H_4$ while the adduct of cyclooctatetraene loses labile fragments again corresponding to $C_2 H_2$ and $C_4 H_4$. This is presumably caused by rupture of the cyclobutene rings and the stability of the fragments associated with the position of the double bond in these rings. The cracking patterns, on the whole, are very similar. There are no examples of mass spectra of this type of compound in the literature, from which the cracking pattern can be studied, and bearing in mind the comments above, all that can safely be said of the unknown adduct is that it is not the cyclooctatetraene adduct, although very similar with the same molecular weight, and probably has a different double bond placement in the cyclobutene ring. This is really a problem for N.M.R.

In the final assessment the assignment of structure (51b) for the unknown adduct rests on I.R. and N.M.R. evidence. The precursor can be (43) or (45) of which the former better agrees with the infrared spectrum. It is therefore tentatively suggested that unknown (24) is bicyclo [4. 2. 0] octa - 1, 3, 6 - triene (43).

CONCLUSION

1, 2, 5, 6 - Tetrabromocyclooctane has been successfully dehydrobrominated with potassium t - butoxide in diglyme to a mixture of isomeric hydrocarbons containing mainly benzocyclobutene, styrene and a compound believed to be bicyclo [4. 2. 0] octa - 1, 3, 6 - triene. Cyclooctatetraene and an unknown compound are present in trace quantities only. The overall yield of benzocyclobutene is 23%. This is a new, two stage synthesis of benzocyclobutene from commercially available starting material, and compares favourably with those previously published.[5, 6, 7, 8]

PART II

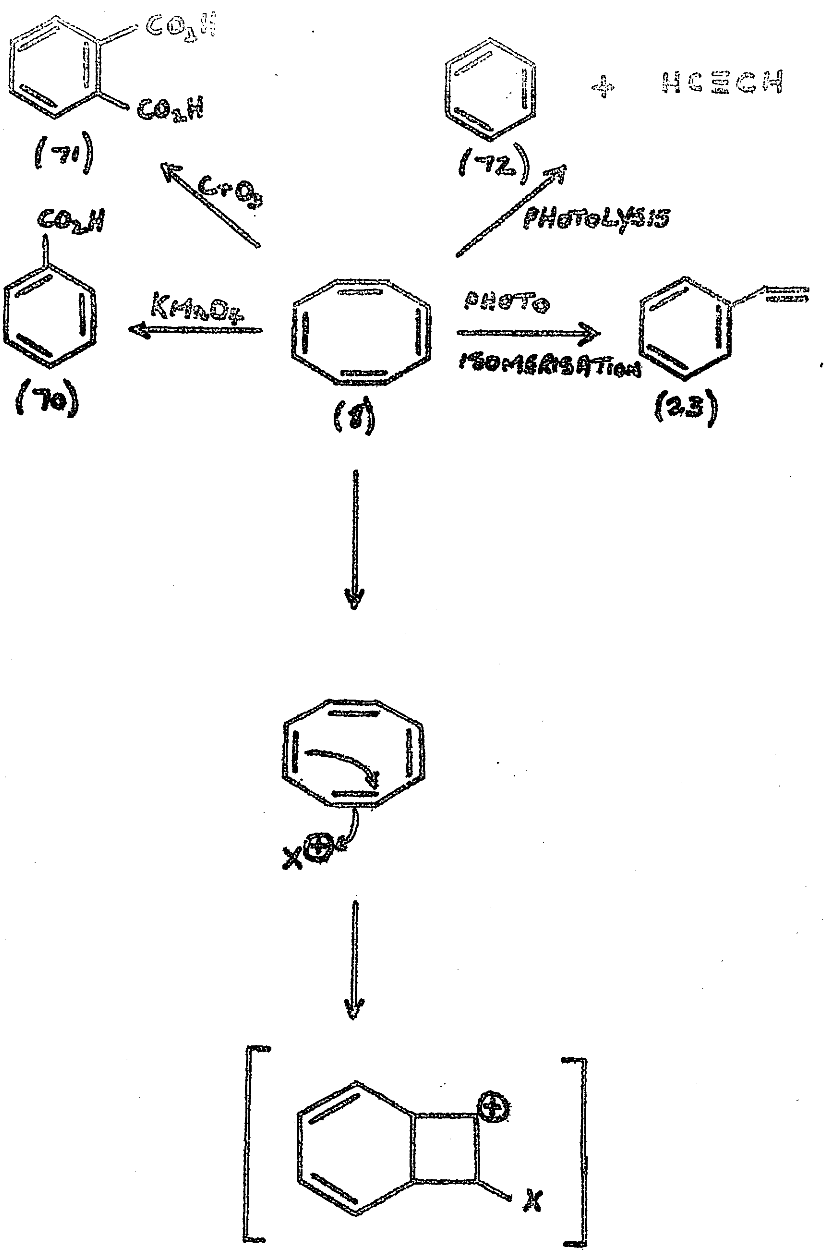
SECTION B

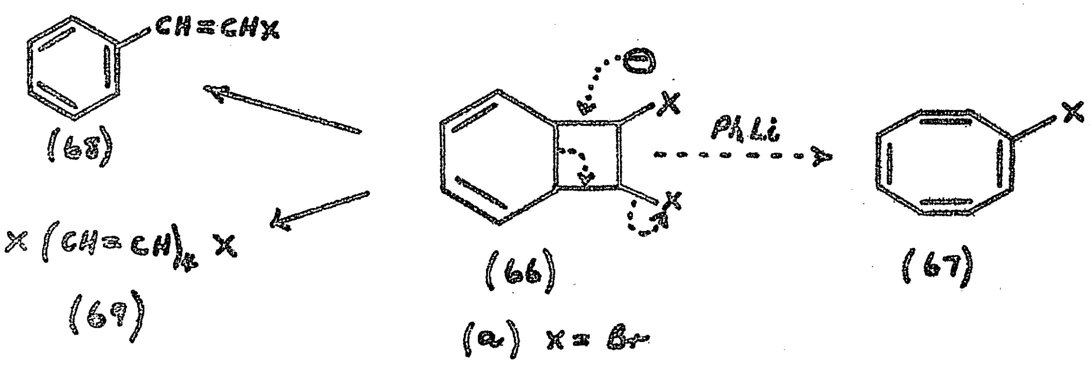
Aromatisation of Cyclooctatetraene.

INTRODUCTION

Cyclooctatetraene (C.O.T.) has attracted considerable attention since Willstatter,[48] in an attempt to create a new non-benzenoid aromatic system, synthesised the molecule and found it devoid of aromatic character. The commercial availability of C.O.T. by the nickel-catalysed tetramerisation of acetylene devised in war-time Germany by Reppe et al.[40] and the many illustrations of its anomalous reactions, by these same authors, provoked an attack, the intensity of which is precedented in chemical history only by the research on benzene itself. The many facets of the chemistry of C.O.T. which were uncovered are amply reviewed by Craig[12] and Raphael.[49]

The presence of C.O.T. in the dehydrobromination product of 1, 2, 5, 6 - tetrabromocyclooctane and the possibility that benzocyclobutene had been produced in the reaction by rearrangement of C.O.T., as elimination product, led us to speculate on the feasibility of direct isomeration of C.O.T. to benzocyclobutene. This speculation is not unfounded as, on reaction, C.O.T. readily forms both bridged and benzenoid compounds. A particularly good illustration of the formation and mobility of the bridged structure is shown in the preparation of cyclooctatetraene monobromide (67a). Halogenation of C.O.T.





(a) $X = Br$

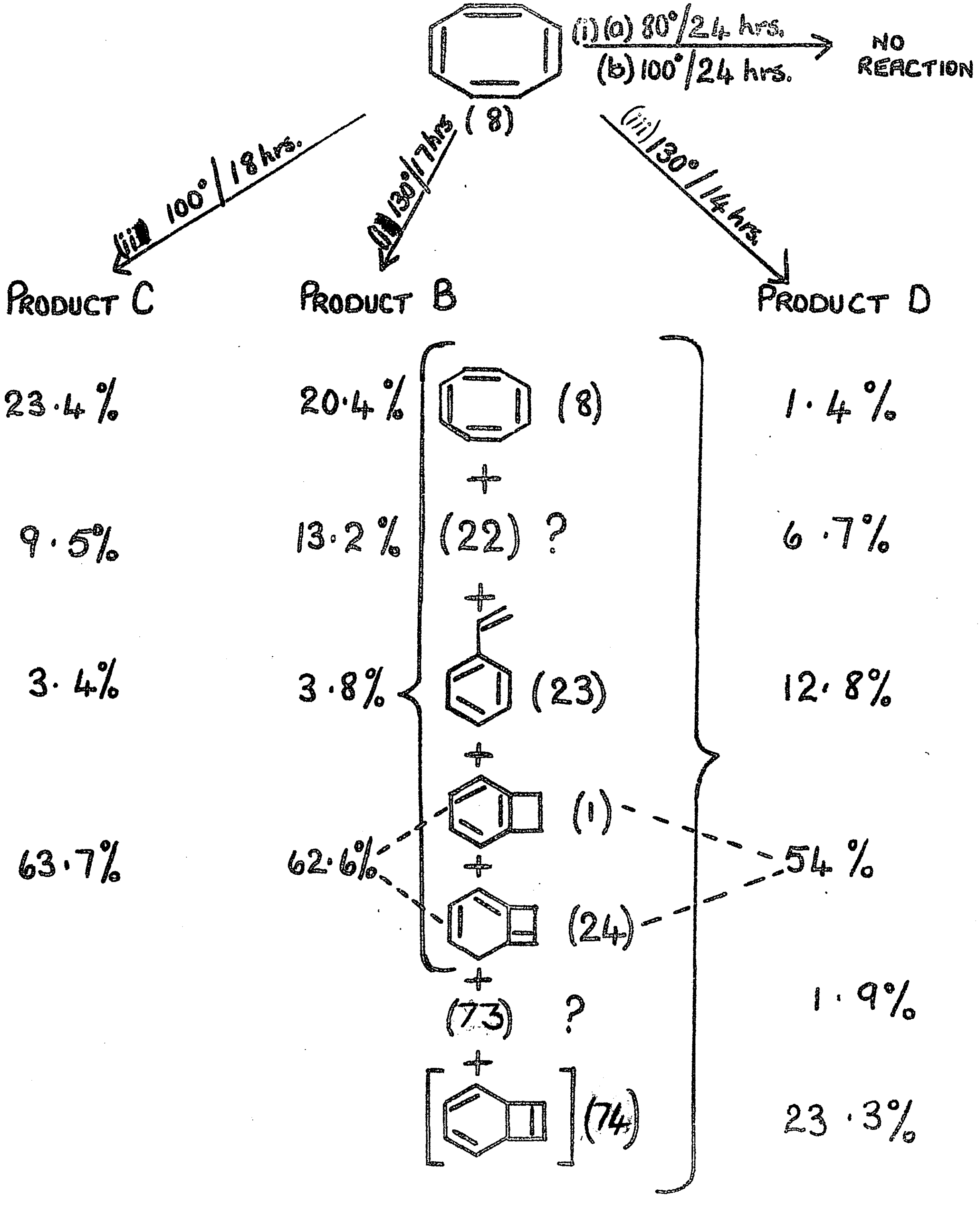
(b) $X = Cl$

(c) $X = CN$

gives the bicyclo system (66), formation of which has been explained by Friess[43] in the case of (66a) as transannular rearrangement of C.O.T. on electrophilic attack to give the carbonium ion (65a) hence to (66a). Treatment of this with phenyl lithium gives (67a) by a process explained by Cope[50] as basic displacement of a proton followed by reversal of the bridging process. Examples of valence tautomerism particularly in regard to Diels-Alder adduct formation have already been dealt with. Permanganate and chromic acid oxidation of C.O.T. yield benzoic (70) and phthalic (71) acids respectively,[40] while pyrolysis of the dichloride (66b) gives β - chlorostyrene (68b).[50, 51] Photolysis of C.O.T. gives benzene (72) plus acetylene, and photoisomerisation yields styrene (23).[52] Ring opening reactions are also known[53] e.g. attempted preparation of the cyanide (66c) from the dibromide (66a) gives the straight chain tetraene (69c).[54]

FLOW SHEET 3

ISOMERISATION EXPERIMENTS ON CYCLOOCTATETRAENE



PRODUCT C	PRODUCT B		PRODUCT D
23·4%	20·4%	(8)	1·4%
9·5%	13·2%	(22) ?	6·7%
3·4%	3·8%	(23)	12·8%
63·7%	62·6%	(1) + (24)	54%
		(73) ?	1·9%
		(74)	23·3%

DISCUSSION

Isomerisation of cyclooctatetraene

Several experiments in which C.O.T. was treated with 10% potassium t - butoxide in diglyme, under varying conditions, are described below, and the results shown opposite.

(i) Treatment of C.O.T. at 80° for twenty-four hours and then at 100° for a further twenty-four hours gave unchanged starting material, which on further treatment at 130° for seventeen hours gave product B.

(ii) Repetition of the attempted isomerisation of C.O.T. at 100° for eighteen hours gave product C. The infrared spectra of products B and C were identical to that of product A from 1, 2, 5, 6 - tetrabromocyclooctane. G.L.C. analyses demonstrated that all three products contained the same four components, C.O.T. (8), unknown (22), styrene (23) and the last peak composed of benzocyclobutene (1) and unknown (24), but in different concentrations (table 1, runs 3, 4, 5; table 2, runs 16, 17, 18, 19). The last peak was collected by preparative G.L.C. using a 1% silicone grease column and its accurate infrared and ultraviolet spectra, previously used to deduce a structure for unknown (24), are shown in figs. 2 and 3 respectively.

C.O.T. is notorious for producing the unexpected, and that this reputation is by no means ill-founded was demonstrated when the isomeration at 130° was repeated.

(iii) Treatment of C.O.T. with 13% potassium t - butoxide at 130° for fourteen hours gave an oil which was separated into three boiling-point ranges. The lowest boiling fraction (product D) displayed a similar infrared spectrum as products B and C, but there were additional peaks at 1600, 1296, 1194 and 1112 $cm.^{-1}$, and G.L.C. analysis (table 1, run 5) revealed the presence of two new components (73) and (74) in trace and *ca*. 23% respectively. There was now only negligible amounts of C.O.T. and unknown (22) but an increase in the proportion of styrene. The relationships between products B, C and D are shown in flow sheet 3.

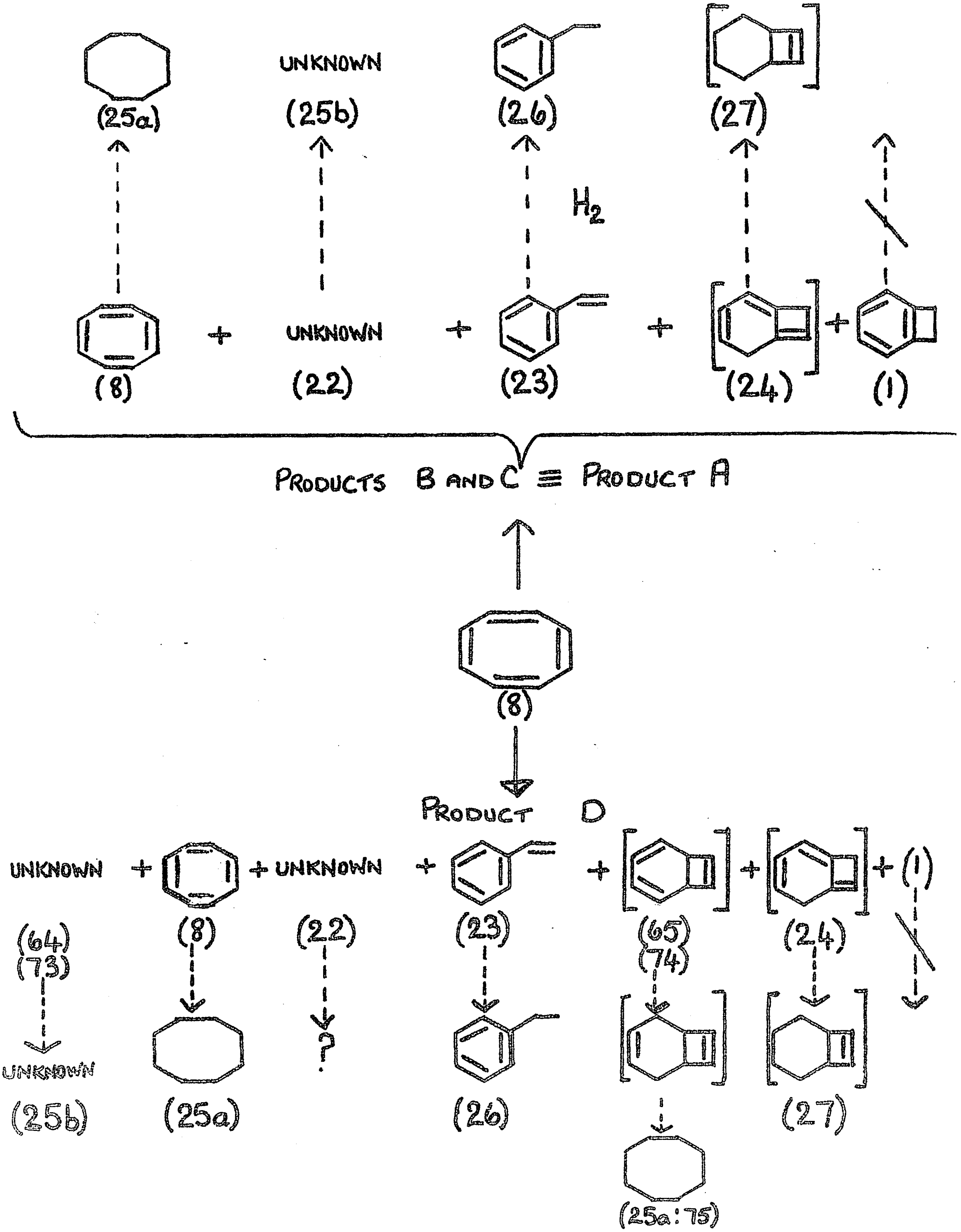
Hydrogenation of product D.

Complete hydrogenation of product D gave peaks corresponding to benzocyclobutene (1) and ethyl benzene (26). Analytical G.L.C. (table 3, runs 23, 24, 25) revealed five peaks, two of which were identified by mixed chromatograms as ethyl benzene and benzocyclobutene. The other three components were (75) in a proportion in agreement with hydrogenation of the new unknown (74), component (27) of the same retention time as hydrogenated unknown (24) in product A, and presumably the co-production of (24) and benzocyclobutene (1) with coincident retention times is also occurring in this case, and component (25b) in trace quantity, also present in hydrogenated product A. The components (75), (27) and (1) were collected by preparative G.L.C. using a 10% Apiezon 'L' column, and the last component identified by infrared as benzocyclobutene. This constitutes a new one stage synthesis of benzocyclobutene in 13% yield.

Component (75) had an infrared spectrum concordant with that of [a]cycloalkane and is probably cyclooctane (25a). From the relative proportions of the other components in unhydrogenated product D, this constituent can only come from component (74). As previously mentioned, Jones[27] has suggested that sodium in alcohol reduction of C.O.T. takes place by initial isomeration to bicyclo $[4.2.0]$ octa - 2, 4, 7 - triene (35) followed by 1, 4 - addition of hydrogen giving the 3, 7 - diene (64), which undergoes further hydrogenation with rearrangement giving all three isomeric cyclooctadienes. This lends some support to the suggestion that cyclooctane (25a) is formed by hydrogenation of bicyclo $[4.2.0]$ octa - 2, 4, 7 - triene present as the new component (74) in product D.

The accurate infrared spectrum of component (27) is summarised and compared with that of ethyl cyclohexane, in table 7. From this spectrum it has previously been tentatively suggested that component (27), present in both hydrogenated products A and D and presumably in B and C, is

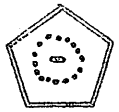
FLOW SHEET 4.


(25a)
UNKNOWN
(25b)
(26)
(27)
H_2
(8)
+
UNKNOWN
(22)
+
(23)
+
(24)
+
(1)
PRODUCTS B AND C ≡ PRODUCT A
(8)
PRODUCT D
UNKNOWN
+
+ UNKNOWN
+
+
+
+ (1)
(64)
(73)
(8)
(22)
(23)
(65)
(74)
(24)
UNKNOWN
(25b)
(25a)
?
(26)
(27)
(25a : 75)

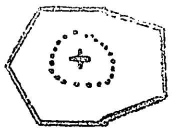
bicyclo [4. 2. 0] octa - 7 - ene formed by hydrogenation of bicyclo [4. 2. 0] octa - 1, 3, 6 - triene (24). The cessation of hydrogenation at this stage may be a consequence of the very rigid cyclobutene structure. The relationships between products A, B, C and D are shown in flow sheet 4.

The mechanism of aromatisation of cyclooctatetraene.

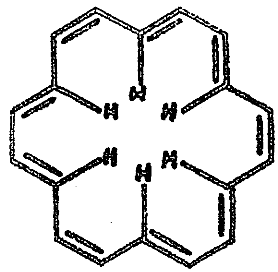
The structure of C.O.T. has been the subject of extensive physical examination by many workers, prominent among whom are Kaufman,[55] Tanaka[56] and Lippencott,[57] and the molecule is known to exist as dn all cis 'tub' structure (8a) with almost completely localised alternating single and double bonds. The generally accepted mode of base-catalysed prototropic rearrangement cannot apply in such a rigid non-planar system and an alternative mechanism must be sought. The problem is to change the rigid localised 'tub' structure into a planar delocalised structure which will permit unhindered movement of electrons. The energy required to do this would necessarily have to be large and some compensatory factor, such as the production of a highly resonance-stabilised aromatic system, must be involved. Huckels application of molecular orbital theory to aromatic compounds led to the prediction that monocyclic molecules containing $4n + 2$ electrons would be aromatic. This has been adequately demonstrated in the cases



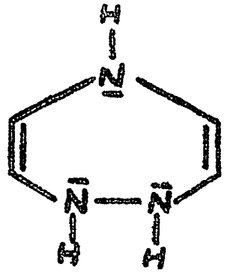
(76)



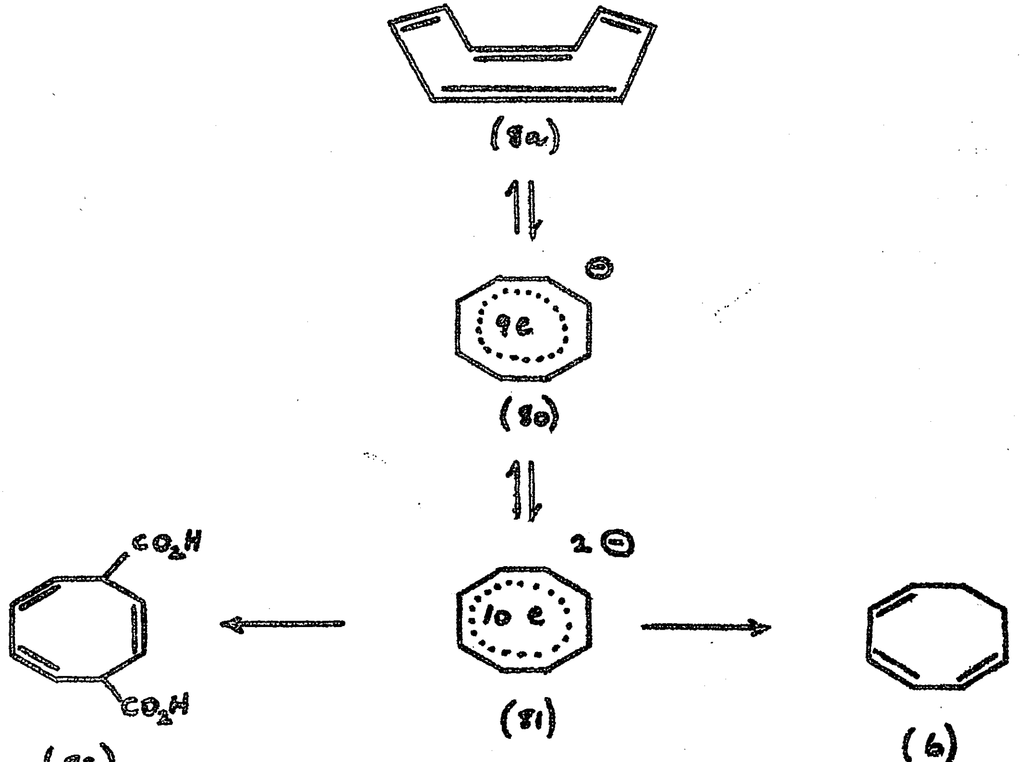
(77)



(78)



(79)



of the cyclopentadienyl anion (76),[58] the cycloheptatrienyl cation (77),[59] and where n >1 in Sondheimer's [60] cyclooctadecanonaene (78) and Allinger's [61, 62] 1, 4, 5 - triazacyclohepta - 2, 6 - diene (79). The aromatic system embodying C.O.T. is the cyclooctatetraenyl dianon (81). This has been prepared by Katz and the N.M.R., U.V., I.R. spectra and the wave-mechanical assessment are in accord with the theory.[58, 63, 64, 65, 66] Katz has further shown that the product of the treatment of C.O.T. with sodium or lithium in tetrahydrofuran is an equilibrium mixture of the 'tub' structure cyclooctatetraene (8a), the planar cyclooctatetraenyl radical anion (80) and the planar cyclooctatetraenyl dianion (81) with the equilibrium lying to the right. The dianion formation has been used to prepare C.O.T. derivatives, thus carbonylation gives cycloocta - 1, 3, 6 - triene - 5, 7 - dicarboxylic acid (82)[67] and oxidation gives cyclooctatriene (6).

In our work when the diglyme solution of potassium t - butoxide was added to the C.O.T. solution there was an instantaneous colour change from colourless to bright purple, reverting to green on standing and back to purple on shaking. It has been noted elsewhere that not all the t - butoxide dissolves in the diglyme but a milky suspension is obtained which slowly settles. The colour change on shaking suggests a reaction between C.O.T. and solid butoxide. Heating produced a deep red solution which persisted for the first hour then slowly darkened. A similar colour change is reported by Wittig[68] in the preparation of the disodio derivative of C.O.T. using trityl sodium - "on mixing the two reaction components there was an immediate deep red colouration which cleared to an orange solution," and is presumably associated with (di) anion formation. On this evidence the mechanism proposed for the formation of the products obtained by base treatment of C.O.T. is initial formation of this aromatic cyclooctatetraenyl dianon (possibly in equilibrium with C.O.T. and the radical anion) which on hydrolysis yields the reported product.

The formation of the same products from both 1, 2, 5, 6 - tetrabromocyclooctane and C.O.T. support the premise that, in the former case, these are formed via C.O.T. and its dianion. It is, however, doubtful if this dianion would form in the presence of <u>t</u> - butanol, although excess <u>t</u> - butoxide is present. Whether the products are formed directly by dehydrobromination or via the dianion remains unknown.

None of the higher boiling fractions obtained with product D from C.O.T. have been investigated. The highest boiling fraction, a low melting solid, is probably the dimer of C.O.T., m.p. 41.5°, described by Haghara[69] and Nyburg.[70]

CONCLUSION

Cyclooctatetraene has been successfully isomerised to a mixture of mainly five components of which C.O.T., styrene and benzocyclobutene have been identified and the structures of the remaining two suggested to be bicyclo [4. 2. 0] octa - 1, 3, 6 - triene (24) and bicyclo [4. 2. 0] octa - 2, 4, 7 - triene (35). The relative amounts of these are dependent on the temperature. In an isomeration at 130° in which all five were produced the yield of benzocyclobutene was 13%. This is the simplest synthesis of benzocyclobutene and the yield compares favourably with those obtained by other routes. It is suggested that the mechanism involves the cyclooctatetraenyl dianion and, in consequence, this is the first time a benzenoid aromatic isomer has been produced from C.O.T. without ring fission.

EXPERIMENTAL

The general points on experimental procedure given at the beginning of the experimental of Part I apply here. Cis, cis - 1, 5 - cyclooctadiene (19) was obtained from the Cities Service and Development Co.[73] as a colourless oil b.p. 152°/760 m.m., $n_D^{20.5°}$ 1.4939, ν_{max}^{film} 3010 (CH = CH), 1644 (C = C), 700 c.m.$^{-1}$ (cis - double bond). All as quoted by the manufacturers.

Pyridinium bromide perbromide[25, 71]

Liquid bromine (100 g., 32.2 m.l., 0.63 mol.) was added with stirring and cooling to a cold solution of pyridine (60 ml., 58.2 g. 0.73 mol.) in 48% hydrobromic acid (120 ml.). The solid product was filtered, washed with glacial acetic acid and recrystallised from the same solvent to give orange needles (144 g., 72%).

1, 2, 5, 6 - Tetrabromocyclooctane (21)

A solution of pyridinium bromide perbromide (120 g., 0.33 mol.) in pyridine/methanol (4 : 1, 400 ml.) was added slowly with stirring to a solution of 1, 5 - cycloctadiene (19) (20 g., 0.185 mol.) in benzene/methanol (1 : 1, 400 ml.) at room temperature, and the mixture allowed to stand overnight.

Most of the methanol was then removed under water pump pressure and the mother liquors added to water (500 ml.) and extracted with ethyl acetate (3 x 300 ml.). The extracts were washed with 6 N hydrochloric acid (2 x 500 ml.) and dried over magnesium sulphate. Most of the ethyl acetate was then removed and the residues crystallised from ethanol to give the tetrabromide as colourless crystals (66 g., 83%), m.p. 147 - 148°. (Found : C, 22.27; H, 2.94. $C_8 H_{12} Br_4$ requires C, 22.46; H, 2.82%). The N.M.R. spectrum was run on a 1 molar solution in chloroform and showed broad absorption between 5.15 - 5.38 (methylenic protons) and 7.0 - 7.95 τ (methine protons), areal ratio ca. 2 : 1.

Dehydrobromination of 1, 2, 5, 6 - tetrabromocyclooctane (21) (Formation of product A.)

A solution of 1, 2, 5, 6 - tetrabromocyclooctane (61 g., 0.14 mol.) in diglyme (300 ml.) was added over thirty minutes with stirring to a solution of potassium t - butoxide (from 38 g. of potassium) in diglyme (300 ml.) under nitrogen at 30°. There was an immediate exothermic reaction with black colouration. Heating was commenced immediately and the temperature of the mixture maintained at 120°, stirring being discontinued after seven hours. An aliquot (28 ml.) was removed after twenty-two hours and on working up as below gave a brown oil (200 mg.). Infrared examination indicated that dehydrobromination and aromatisation had occurred. The reaction mixture was therefore cooled, poured into water (750 ml.), extracted with 40 - 60° petrol (4 x 400 ml.), the extracts washed with water (6 x 500 ml.) and dried over magnesium sulphate. Removal of the solvent through a 15" Dufton column and fast distillation gave a colourless liquid (product A) (6 g.), b.p. 135 - 145°/760, 44 - 46°/13 mm., $\nu_{\text{max.}}^{\text{film.}}$ and 3010, 1622, 700 and 672 cm.$^{-1}$ (unsaturation, <u>cis</u> - double bonds) $\lambda_{\text{max.}}^{\text{EtOH}}$ 235 ($\mathcal{E}$ 918), 260 (675), 266 (644), 272 mμ (467). Spectrum broad see fig. 1.

<u>Gas-liquid chromatography of product A.</u> on Apiezon 'L', squalane, silicone grease and silver nitrate columns (table 2, runs 6, 7, 8 and 9) showed that product A contained at least four components of which two were identified as cyclooctatetraene and styrene by mixed chromatograms (table 2, runs 14, 15). The peak of longest retention time was collected by preparative G.L.C. using a 1% silicone grease column at 61°, Argon flow rate of 0.25 l./min., R_T 4.3 min. Analytical G.L.C. of the collected fraction on 10% apiezon 'L'/celite at 71°, flow rate of 45 ml./min. showed only one peak R_T 19.6 min. Ultraviolet spectrum (fig. 3) showed $\lambda_{\text{max.}}^{\text{EtOH}}$ 260 (log $\mathcal{E}$ 3.34), 266 (3.42), 272 mμ (3.38) identical to that of benzocyclobutene.

The mass spectrum had an identical cracking pattern to that of both benzocyclobutene and cyclooctatetraene,[30] of molecular weight 104.

Alkaline permanganate oxidation of benzocyclobutene.

Benzocyclobutene (kindly supplied by Prof. Horner, Mainz) (59 mg.) was heated at 100° for two hours with potassium permanganate (1 g.) and sodium bicarbonate (0.1 g.) in water/*t* - butanol (4 : 1, 15 ml.) solution. The reaction mixture was then cooled, acidified with 6 N sulphuric acid and heated for a further thirty minutes. Sufficient solid sodium bisulphite was added to remove the precipitated manganese dioxide, more water (10 ml.) added and the solution extracted with ether (3 x 15 ml.). The extracts were washed with saturated salt solution (2 x 20 ml.), dried over magnesium sulphate and the solvents removed to give a white solid (66 mg., 70%)

Alkaline permanganate oxidation of product A.

Product A (61 mg.) oxidised as above gave a white solid (33 mg.) which sublimed at 130 - 160°/760 mm. as phthalic anhydride, m.p. and mixed m.p. 130°. (Found : C, 64.82; H, 3.37. Calc. for $C_8H_4O_3$: C, 64.87; H, 2.72%). Direct comparison with the oxidation of pure benzocyclobutene showed that product A contained 48.4% of benzocyclobutene corresponding to a yield of 20% from 1, 2, 5, 6 - tetrabromocyclooctane.

Infrared estimation of the content of benzocyclobutene in product A.

The optical density of a carbon disulphide solution of product A was directly compared with the optical densities obtained from solutions of authentic benzocyclobutene in the same solvent, using the O - disubstitution band at 714 cm.$^{-1}$

Weight of product A/10 ml. CS_2 solution	Optical Density
19.1 mg.	0.120
Weight of benzocyclobutene/10 ml. CS_2 solution	
11.74 mg.	0.136
23.00 mg.	0.265

Product A therefore contains 55% of benzocyclobutene corresponding to a yield of 23% from 1, 2, 5, 6 - tetrabromocyclooctane.

Hydrogenation of product A. (flow sheet 1).

Product A (614 mg.) in cyclohexane (10 ml.) was added via a hypodermic syringe and serum cap to a prehydrogenated mixture of 5% palladium/charcoal (50 mg.) in cyclohexane (70 ml.) and the resulting mixture hydrogenated. The hydrogen uptake was 180 ml., 0.008 mol. Most of the solvent was removed through an 8" Vigreux column to give a colourless oil

ν_{max}^{film} 779, 712 (aromatic γ - CH, as in benzocyclobutene), 750 and 696 (as in ethyl benzene) 742 sh. (unknown) and 698 cm.$^{-1}$ (cis - double bond), other regions complicated by cyclohexane $\lambda_{max.}^{EtOH}$ 240 - 245 (sh.), 260, 266 and 272 mμ .

Ethyl benzene $\lambda_{max.}^{hexane}$ (log ε). 248 (2.2), 255 (2.4), 261 (2.4), 268 (2.3)^{72}

Analytical G.L.C. of hydrogenated product A on 10% Apiezon 'L' showed four peaks (table 3, run 20) two of which were assigned to ethyl benzene and benzocyclobutene on the basis of mixed chromatograms (table 3, runs 21, 22, 24, 26).

Preparative scale G.L.C. on the Griffin and George apparatus using a 10% Apiezon 'L' column at 80° with a flow rate of 2.6 l./min. was only partially successful in that ethyl benzene was effectively removed. The infrared spectrum of the resulting oil had peaks at 778, 714 (benzocyclobutene) and 1660, 698 cm.$^{-1}$ (cis - double bond). Further attempts were made impossible because of instrument failure.

Diels - Alder adduct formation of product A. (Flow sheet 2).

Product A (1.72 g.) in benzene (6 ml.) was refluxed with maleic anhydride (0.87 g.) for two hours and allowed to stand in the cold for two days when long needle crystals separated. The supernatant liquors were removed and successively titurated with 40 - 60° petrol until solid precipitation ceased. The white precipitates were centifruged from the petrol-benzene solution and combined with the needle crystals. Most of the solvents were removed from the mother liquors, under water pump pressure, to give a brown oil containing some anhydride, $\nu_{max.}^{film}$ 1760, 1840 cm.$^{-1}$. Distillation gave an oil, b.p. 49 - 55°/15 mm., $\nu_{max.}^{film}$ 1610, 1475 (aromatic C = C), 778, 713 (*o* - disubstitution in benzocyclobutene), 982, 900, 694 cm.$^{-1}$ (styrene).

Analytical G.L.C. (table 1, run 2) showed the same four peaks as untreated product A, but the area of the last peak had diminished relative to the others. The main peaks (23) and (1) were separated by preparative G.L.C. using a 10% Apiezon 'L' column and the infrared spectra of the collected oils were found to be identical to those of styrene and benzocyclobutene respectively.

The adduct of product A. (51b)

The combined solid products obtained in the above experiment sublimed at 100 - 120°/0.1 mm. as white needles m.p. 145° (sublimation to cover slip at 135°). (Found : C, 71.24; H, 5.20. $C_{12}H_{10}O_3$ requires C, 71.28; H, 4.99%). The infrared spectrum is shown in fig. 4 and the tentative peak

ass peak corresponding to a molecular weight of 202, ($C_{12}H_{10}O_3$).
peak corresponding to a molecular weight of 202, ($C_{12}H_{10}O_3$).
N.M.R. in chloroform (fig. 5) showed peaks at 3.62 - 3.51 (three peaks; olefinic protons), 7.25 (twin peak; methine protons α - to anhydride), 7.40 (allylic protons) and 8.4 - 7.5 τ (diffuse peaks; methylenic protons). The area of peaks associated with methine and allylic protons was twice that associated with the olefinic protons as measured by weight.

The maleic anhydride adduct of cyclooctatetraene (51a).

Method A.[40] Cyclooctatetraene (537 mg.) was heated with maleic anhydride (591 mg.) in O - diclorobenzene at 160 - 170° for one hour. On cooling a yellow solid separated. The solvent was removed by washing with ether and yellow crystals (789 mg., 74%) were obtained. Sublimation of these at 100 - 120°/0.1 mm. gave colourless crystals m.p. 168° as in literature[40] sublimation to cover slip at 140°) (Found : C, 71.25; H, 5.40. Calc. for $C_{12}H_{10}O_3$: C, 71.28; H, 4.99%) The infrared spectrum is shown in fig. 4, and the group frequencies, and their tentative assignments, coincident in the spectrum of the adduct of product A, in table 6. The mass spectrum showed no stable ion above m/e 130. The cracking pattern indicated loss of C_2H_2, C_4H_4, benzene and C_2O_3 in accord with the structure. The N.M.R. spectrum in chloroform showed peaks at 4.2 (olefinic protons), 7.01 (protons allylic to the double bond of the cyclobutene ring), 7.29 (protons α- to anhydride), 7.92 τ (allylic protons at bridge head) and no signals associated with methylenic protons. The ratio of the areas of the peaks associated with olefinic to non-olefinic protons was ca. 2 : 3, as required by the formula.

Method B.

Cyclooctatetraene (130 mg.) was refluxed with maleic anhydride (137 mg.) in benzene (3 ml.) for two hours and the reaction mixture allowed to stand in cold for a further twenty hours. Tituration with benzene gave a brown solid (180 mg.) which on sublimation at 100 - 120°/0.15 mm. separated into two fractions m.p. 53° (maleic anhydride) and 166-7° (the required adduct). Visually it was apparent that unchanged maleic anhydride was present to an extent $>50\%$. Infrared spectrum of crystals m.p. 166-7° was identical to that of the adduct prepared as in method A.

The maleic anhydride adduct of benzocyclobutene[45, 46] (62)

Benzocyclobutene (80 mg.) was heated with maleic anhydride (91 mg.) at 200° for ten hours in a sealed tube. The contents were then extracted with chloroform and the solvent removed to give a brown solid (154 mg., 96%) sublimed twice at 120°/0.2 mm. as colourless crystals of 1, 2, 3, 4 - tetrahydro - 2, 3 - naphthoic diacid anhydride (62) m.p. 186.5 - 187.5° as in literature.

EXPERIMENTAL

Isomerisation of Cyclooctatetraene

(i) Formation of product B.

Redistilled cyclooctatraene (b.p. 42°/17 mm., 6.2 g., 0.05 mol.) was heated with potassium t - butoxide (from 10 g. potassium) and diglyme (300 ml.) under nitrogen, with stirring, at ca. 80° (100° bath temperature), for twenty hours. Extraction with pentane and work up, as usual, gave an oil (4.5 g.), b.p. 31 - 32°/11 mm., infrared spectrum almost identical to cyclooctatetraene. This product (4 g.) was treated again under the same basic conditions, heating this time at 100° (110° bath temperature), without stirring, for twenty-four hours and gave starting material (2.6 g.) containing a little aromatic material $\nu^{\text{film}}_{\text{max.}}$ 1600, 1475 cm.$^{-1}$. Further treatment of this with potassium t - butoxide (18 g.) in diglyme (180 mls.) for seventeen hours at 130° (140° bath temperature) again without stirring gave an oil. (product B; 730 mg.). Infrared spectrum very similar to that of the dehydrobromination product A of 1, 2, 5, 6 - tetrabromocyclooctane.

Analytical G.L.C. of product B (table 1, run 3) revealed the presence of four peaks with the same retention times as cyclooctatetraene (8), unknown (22), styrene (23), and benzocyclobutene (1) present as ca. 20, 13, trace and 63% respectively, of the mixture.

(ii) Formation of product C.

Cyclooctatetraene (2 g., 0.019 mol.) was treated as above with potassium t - butoxide (6 g.) in diglyme (60 ml.) at 100° for eighteen hours to give a brown oil (1.96 g.), distilled to a colourless oil (product C), b.p. 70°/25 mm., infrared spectrum identical to that of product B, $\lambda^{EtOH}_{max.}$ (ε), 251 sh. (615), 259 (610), 265 (606) and 272 mμ (590). Analytical G.L.C. of product C (table 1, run 4) showed four peaks three of which were identified by mixed chromatograms (table 2, runs 11, 12, 13, 16, 17, 18) as cycloctatetraene (8), styrene (23) and benzocyclobutene (1). The composition of products C and A was also shown to be the same by a mixed chromatogram (table 2, run 19).

Separation and spectral characteristics of the main peak (benzocyclobutene and unknown (24)) in product C.

The main peak was collected by preparative G.L.C. using a 1% silicone grease column and the eluate analysed as one peak on 10% Apiezon 'L' at 71°, Argon flow rate of 43 ml./min., R_T 20.8 min. The accurate infrared and ultraviolet spectra of the collected sample and of benzocyclobutene are shown in figs. 2 and 3, respectively. The salient absorption bands in the infrared spectrum of unknown (24), obtained by subtraction and their tentative assignments are tabulated in table 4.

(iii) Formation of product D.

Cyclooctatetraene (6.14 g., 0.059 mol.) in diglyme (100 ml.) was added all at once to a solution of potassium t - butoxide (from 20 g. of potassium) in diglyme (400 ml.) There was an immediate colour change to bright purple which turned green on shaking but reverted to purple on standing. The mixture was heated at 130° (140° bath temperature) under nitrogen without stirring for fourteen hours when the infrared spectrum of an aliquot showed that the reaction had occurred. The reaction mixture was consequently cooled, extracted with pentane (4 x 200 ml.) and worked up in the usual way to give a dark brown oil 5.92 g. Fast distillation of this gave three fractions:

(a) product D (2.1 g.), b.p. 50 - 70°/22, 140 - 153°/760 mm., infrared spectrum similar to that of products A, B and C, with new bands at 1600 (aromatic C = C), 1296, 1194 and 1122 cm.,$^{-1}$

(b) straw coloured oil (200 mg.), b.p. 140 - 170°/22 mm., $\nu^{\text{film}}_{\text{max.}}$ 3010 w, 2900 s, 2800 s, 1612 w, 1600 w, 1580 w, 775 m, 755 m, 735 s, 708 m, 700 s cm.$^{-1}$, (a mixture containing product D). This product was not investigated.

(c) brown oil (360 mg.), solidified on standing, b.p. 100 - 120°/0.05 mm., $\nu^{\text{film}}_{\text{max.}}$ 3300 m (bonded - OH), 3010 s (CH = CH), 1595 m (aromatic C = C?), 1355 m (- OH), 755 s (γ - CH mode), 696 s cm.$^{-1}$ (cis - double bond). This product possibly contains the dimer of cyclooctatetraene, m.p. 41.5°.[69, 70] There was a dark brown resinous residue (1.06 g.) from this distillation.

Estimation of the benzocyclobutene content of product D by infrared analysis.

The optical density of the infrared absorption band at 714 cm.$^{-1}$ was determined for known concentrations of product D in carbon disulphide solution and compared with the absorption of the same band in authentic benzocyclobutene. (ε 240) in 0.5 mm. cells. The results are given below:

	Weight mg. of product D/10 ml. CS_2 solution	Optical density	% benzocyclobutene.
(a)	19.74	0.051	22.3
(b)	119.8	0.47	20.4

The mean benzocyclobutene content of product D was therefore 22.4% corresponding to a yield of 13.3% from cyclooctatetraene.

Analytical G.L.C. of product D. (table 1, run 5) indicated a six-component system consisting of unknown (73), cyclooctatetraene (8), unknown (22), styrene (23), unknown (74) and a component of the same retention time as benzocyclobutene (1).

Hydrogenation of product D.

Product D (486 mg.) was completely hydrogenated over 5% palladium on charcoal (59 mg.) in cyclohexane (30 ml.). Removal of most of the cyclohexane over a Vigreux column followed by micro-distillation gave a colourless oil (510 mg.). The infrared spectrum was dominated with peaks associated with ethyl benzene (750, 696 cm.$^{-1}$) and benzocyclobutene (778, 713 cm.$^{-1}$) the other regions masked by the cyclohexane still present.

G.L.C. of hydrogenated product D.

Analytic G.L.C. (table 3, run 23) indicated the presence of five components, of which ethyl benzene (26) and benzocyclobutene (1) were identified by mixed chromatograms (table 3, runs 24, 25, 26). The three main components were collected by preparative scale G.L.C. using a 10% Apiezon 'L' column and the infrared spectra of the resulting oils found to be (in order of increasing R_T)

(a) $\nu_{max.}^{CS_2}$ 2900, 2866, 2800 and 835 cm.$^{-1}$ very similar to that of cycloheptane.

(b) The infrared spectrum of this fraction is tabulated and compared with that of ethyl cyclohexane in table 7. The assignments are tentative.

(c) The ultraviolet and infrared spectra of this fraction were identical to those of benzocyclobutene (figs. 1 and 2).

Table 1

Gas-liquid chromatographic analysis of the C_8 Hydrocarbon mixtures.

	(73)					(8)					(22)					(23)					(74)					(1) and/or (24)				
	R_T	R_L*	Area	A_L+	%	R_T	R_L	Area	A_L	%	R_T	R_L	Area	A_L	%	R_T	R_L	Area	A_L	%	R_T	R_L	Area	A_L	%	R_T	R_L	Area	A_L	%
	(min)		(sq.cm)																											
Run 1						22.9	0.61	1.4	0.036	2.9	24.4	0.65	1.8	0.046	3.8	28.6	0.77	5.3	0.14	11.2						37.3	1	39	1	82.1
Run 2						23.6	0.6	5.9	0.13	8.1	24.9	0.63	1.9	0.04	2.6	30.2	0.77	16.5	0.35	22.9						39.4	1	47.9	1	66.3
Run 3						14.2	0.62	9.1	0.39	20.4	15	0.65	5.9	0.21	13.2	17.9	0.78	1.7	0.06	3.8						23	1	28	1	62.6
Run 4						15.5	0.62	12.3	0.37	23.4	16.2	0.65	5.0	0.15	9.5	19.4	0.78	1.8	0.05	3.4						24.8	1	33.6	1	63.7
Run 5	16.3	0.53	0.7	0.04	1.9	18	0.59	0.5	0.03	1.4	19.4	0.64	2.4	0.12	6.7	23.8	0.78	4.6	0.24	12.8	27.1	0.89	8.4	0.43	23.3	30.6	1	19.4	1	53.9

* Retention time relative to the last peak.

\+ Area relative to that of the last peak.

Run 1. Dehydrobromination product of 1, 2, 5, 6- tetrabromocyclooctane at 72°, 25.ml. ø

Run 2. Dehydrobromination product of 1, 2, 5, 6- tetrabromocyclooctane after removal of maleic.anhydride adduct at 68°, 25 ml.

Run 3. Isomerisation product B of cyclooctatetraene at 74°, 35 ml.

Run 4. Isomerisation product C of cyclooctatetraene at 71°, 37 ml.

Run 5. Isomerisation product D of cyclooctatetraene at 69°, 33 ml.

ø Argon flow rate in ml./min.

Table 2.

Gas-liquid chromatographic analysis.

	(8)		(22)		(23)		(1) and/or (24)	
	R_T (min)	R_L	R_T	R_L	R_T	R_L	R_T	R_L
Run 6.			15.5		18.1		23.8	
Run 7.			23.4		25.5		34.2	
Run 8.			4		4.7		5.9	
Run 9.							33	
Run 10.	23.4	0.57	26.6	0.65	31.7	0.77	40.9	1
Run 11.	-	-	-	-	30.5	-	-	-
Run 12.	23.6	-	-	-	-	-	-	-
Run 13.	-	-	-	-	-	-	36.9	-
Run 14.	-	-	25.2	0.65	29.4	0.76	38.8	1
Run 15.	24.8	0.59	26.8	0.64	32.5	0.78	41.7	1
Run 16.	15.5	0.62	16.2	0.65	19.4	0.78	24.8	1
Run 17.	15.6	0.62	16.3	0.65	19.6	0.78	25.1	1
Run 18.	14.1	0.62	Sh	-	17.8	0.78	22.8	1
Run 19.	13.7	0.61	14.6	0.66	17.3	0.77	22.4	1

Run 6.	Dehydrobromination product of 1, 2, 5, 6- tetrabromocyclooctane on 10% Apl. at 71°, 43 ml.
Run 7.	As above on 10% squalane at 71°, 38 ml.
Run 8.	As above on 5% silicone grease at 71°, 43 ml.
Run 9.	As above on 20% silver nitrate/triethylene glycol at 71°, 43 ml.
Run 10.	As above on 25% Apl. at 67°, 43 ml.
Run 11.	Styrene on 25% Apl. at 68°, 43 ml.
Run 12.	Cyclooctatetraene on 25% Apl. at 67°, 43 ml.
Run 13.	Benzocyclobutene on 10% Apl. at 72°, 23 ml.
Run 14.	Dehydrobromination product plus styrene on 25% Apl. at 68°, 43 ml.
Run 15.	Dehydrobromination product plus cyclooctatetraene on 25% Apl. at 67°, 43 ml.
Run 16.	Isomerisation product C of cyclooctatetraene on 10% Apl. at 74°, 35 ml.
Run 17.	As above plus benzocyclobutene on 10% Apl. at 74°, 35 ml.
Run 18.	As above plus cyclooctatetraene on 10% Apl. at 71°, 34 ml.
Run 19.	As above plus isomerisation product C on 10% Apl. at 71°, 32 ml.

Table 3.

Gas-liquid chromatographic analyses on 10% Apiezon 'L'.

	(26)					(66)					(25)					(27)					(1)				
	R_T	R_L	Area	A_L	%	R_T	R_L	Area	A_L	%	R_T	R_L	Area	A_L	%	R_T	R_L	Area	A_L	%	R_T	R_L	Area	A_L	%
Run 20.	20.3	0.55	1	0.19	5.8	-	-	-	-	-	26.1	0.71	1	0.19	5.8	31.2	0.85	10	1.89	57.8	36.7	1	5.3	1	30.7
Run 21.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	36.9	-	-	-	-
Run 22.	17.3	0.52	†	-	-	-	-	-	-	-	23.7	0.71	-	-	-	27.7	0.83	-	-	-	33.3	-	-	-	-
Run 23.	35	0.55	5.0	0.16	7.0	38.2	0.60	18.1	0.57	25.2	49.8	0.69	6.0	0.19	8.4	52.3	0.83	11	0.35	15.3	63.2	1	31.6	1	44.1
Run 24.	33.5	0.56*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	60.*	-	-	-	-
Run 25.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	57.3	-	-	-	-
Run 26.	30	0.56	-	-	-	32.8	0.61	-	-	-	37.5	0.70	-	-	-	44.7	0.83	-	-	-	53.7	1	-	-	-

Run 20. Hydrogenated product A (from the dehydrobromination of 1, 2, 5, 6- tetrabromocyclooctane) at 72°, 25 ml.

Run 21. Benzocyclobutene at 72°, 23 ml.

Run 22. Benzocyclobutene plus hydrogenated product A at 72°, 22 ml.

Run 23. Hydrogenated product D (from the isomerisation of C.O.T.) at 70°, 16 ml.

Run 24. Ethyl benzene at 70°, 17 ml.

Run 25. Benzocyclobutene at 70°, 17 ml.

Run 26. Hydrogenated product D plus ethylbenzene plus benzocyclobutene at 70°, 18 ml.

* Extrapolated.

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PART III

Stereomutation effects during the catalytic hydrogenation of undeca-1, 7-diyne.

INTRODUCTION

The chief interests in the catalytic hydrogenation of acetylenes are the selectivity of the process, and in the case of disubstituted acetylenes, the stereochemical course of the reaction. It is this latter phenomenon which is important to this part of the thesis.

In an attempt to reach a better understanding of the processes involved in heterogeneous catalysis, Farkas and Farkas[1] in 1937 reviewed the stereochemistry of the hydrogenation of the C–C triple and double bonds. Other reviews dealing with aspects of this problem have since been compiled by Campbell,[2] Eley,[3] Crombie,[4] Trapnell,[5] Bond,[6] and Burwell.[7]

For many years it was thought that hydrogenation of a disubstituted acetylene gave exclusively the cis-olefin.[8, 9, 10, 11] However, as examples of hydrogenations giving isomeric cis, trans-mixtures began to appear,[12, 13] ideas were altered and various explanations were put forward to account for the formation of trans-olefin. Salkind[14] found that, in the hydrogenation of 1, 1, 4, 4-tetramethylbut-2-yne-1, 4-diol with colloidal palladium, the amount of cis-olefin present was proportional to the rate of hydrogen uptake. He considered that the amount of catalyst used was important in determining the relative proportions of cis and *trans*-isomers formed. Bourguel[10a] suggested that the prime product in any catalytic hydrogenation of a disubstituted acetylene was always the *cis*-olefin, and that this might undergo stereochemical conversion to the *trans* in the presence of the hydrogenation catalyst. Such a conversion would be favoured by a slow hydrogenation velocity thus explaining Salkind's results. This premise could, however, not be established.

Actually, many compounds reported to be pure *cis* must have been mixtures[15, 16] because, before the advent of spectroscopic and chromatographic techniques, analysis of isomeric *cis*, *trans*-mixtures relied upon isolation techniques. Many products thought to be pure *cis* have now been shown to contain 5-20% of the trans-isomer.[15, 16] Thus Sondheimer[17] has found that half-hydrogenation of hex-3-ynol with 5% palladium on calcium carbonate gives an 80:20 *cis*, *trans*-mixture.

In some cases the *trans*-isomer is definitely formed by isomerisation after reaction. Cadiot[18] has demonstrated that in the hydrogenation of 1, 1, 4, 4-tetraphenylbut-2-yne-1, 4-diol, although reduction stops sharply at the olefinic stage, the catalyst continues to catalyse the rearrangement of *cis* to *trans*-glycol. In the case of acetylenes devoid of adjacent substituents which might interact during the hydrogenation, there is, however, no conclusive evidence as to whether the observed *trans*-olefin is an initial product of the reaction or, whether it is formed by isomerisation of the cis-olefin.

Although this cis to trans isomerisation is mechanistically very important, the problem has only received extensive attention in the field of unsaturated fatty acids where it is technically important. Feuge[19] and his colleagues have found that in the hydrogenation of methyl oleate at 200° with nickel, there is present 38% of the trans-ester at 10% hydrogenation to methyl stearate. Beyond about 50% reduction, the cis and trans forms are in equilibrium (1:2). If the hydrogen is replaced by nitrogen the amount of cis to trans isomerisation is greatly reduced, but occurs at a reasonable rate at 290°.[20] The same reduction also takes place over platinum black at 170° and again in the absence of hydrogen the rate is very much reduced.[21, 22, 23] This may be a case of the well-known high temperature isomerisation of olefins over nickel and it is doubtful if it would occur over palladium at room temperature.

Young and his co-workers[24] have examined the reduction of butadiene over 5% palladium on barium sulphate and found that after ca. 70% hydrogenation the product consists of 5% but-1-ene, 75% trans- and 20% cis-but-2-ene which is in remarkable agreement with the equilibrium mixture expected from thermodynamic considerations. The product composition depends on the catalyst, e.g. colloidal palladium and platinum alone give 50–70% of but-l-ene, but the trans-isomer still predominates in the cis-trans mixture. The isomerisation is little affected by temperature, and does not occur in the absence of hydrogen. Similarly, Siegel[25] has shown that isomerisation of various dimethyl cyclohexenes over platinum oxide does not occur in the absence of hydrogen. Thus there is a measure of agreement in that these isomerisation effects are dependent on the hydrogen pressure[25] and temperature.[26]

Large amounts of trans-isomer have been encountered by Loev[27] in the hydrogenation of chlorododec-7-yne with 10% palladium on charcoal or 5% palladium on calcium carbonate. The same reduction using Lindlar catalyst gave substantially pure cis-olefin. A particularly good example of the anomalies present in the hydrogenation literature is provided by Elsner and Paul:[28] they claimed spectroscopically pure cis-octadecenes by hydrogenation of all the possible octadecynes over palladium on starch.

There is an almost infinite variety of catalyst, catalyst concentration, support, solvent, temperature and hydrogen pressure described in the literature and, at the present time, it does not seem feasible to elucidate, from that source, the factors involved in the cis-trans isomerisation of olefins produced by catalytic hydrogenation of acetylenes. The question remains as to whether any trans-olefin is a direct product of the hydrogenation step.

Stereomutation of undec-4-ene on 10% Pd-C (Baker) in cyclohexane at room temperature.

Case	a	b	c	d
% Catalyst	2.3	1.7	2.1	8.4
time (mins)	0 30 60 120	0 39 60 90 120	0 18	0 15 30 50 80 120
% molar hydrogen absorption	5	No absorption	0 98	0 17 42 58 81 94
% trans in ethylenic product*	6.6 50 71 74	68 70 72 72 72	100-	6.6 58 55 50 37 23

* The percentage trans given for zero time is that of the undec-4-ene before addition to hydrogenation flask.

$$\begin{tikzcd}
\underset{\text{I}}{CH_3(CH_2)_2C\equiv C(CH_2)_4C\equiv CH} \arrow[r] & \underset{\text{II}}{CH_3(CH_2)_2C\equiv C(CH_2)_4CH=CH_2} \arrow[d] \\
\underset{\text{IV}}{CH_3(CH_2)_2CH=CH(CH_2)_5CH_3} & \underset{\text{III}}{CH_3(CH_2)_2CH=CH(CH_2)_4CH=CH_2} \arrow[l]
\end{tikzcd}$$

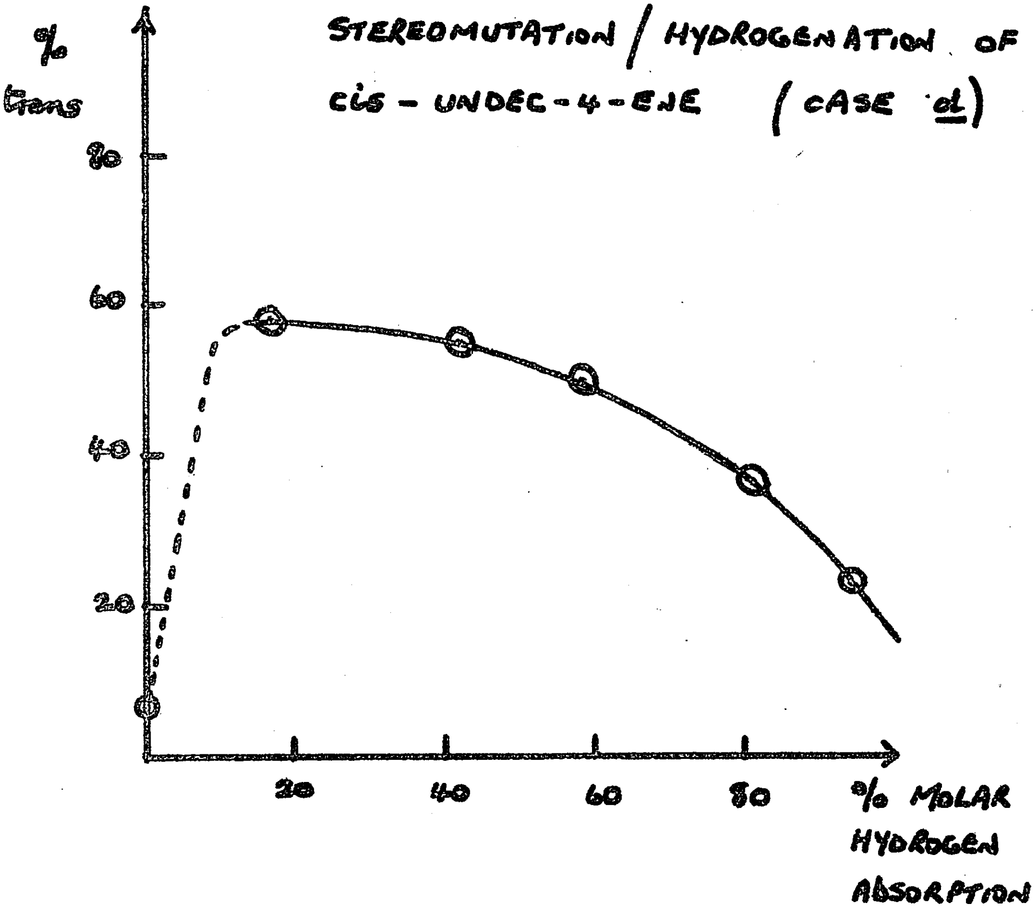
DISCUSSION

The present work[29] is a continuation of that of Dobson,[30] Eglinton, Krisnamurti[31] and Raphael. They found that a surprisingly high amount (ca. 50%) of trans-undec-4-ene (IV) was produced from undeca-1, 7-diene (III) during the step-wise catalytic hydrogenation of undeca-1, 7-diyne (I) to undecane.

One obvious explanation of these results involves stereomutation of initially formed cis-undec-4-ene at the catalyst surface. This simple idea has been discounted in the past[7, 32] in view of the findings that cis-ethylenes did not undergo stereomutation in contact with the catalyst alone under these conditions. This point has been confirmed in the present case by the observation that no stereomutation occurred when a solution of cis-undec-4-ene was shaken in an atmosphere of air or nitrogen with palladium-charcoal catalyst suspended in cyclohexane and derived in the following ways: untreated; prehydrogenated; used initially in a simple hydrogenation. However, it was found that stereomutation did occur when the same mixture was agitated in an atmosphere of hydrogen.[24, 25] This could be shown in a particularly striking manner when the amount of catalyst used was reduced to such an extent that virtually no hydrogenation of the double bond occurred. In such circumstances substantially pure cis-undec-4-ene was transformed in one hour at room temperature into a mixture

FIG. 1.

STEREOMUTATION / HYDROGENATION OF
cis - UNDEC-4-ENE (CASE *d*)



containing ca. 70% of the trans-isomer (table 1, case a), at which point no further stereomutation seemed to occur (cases a and b). This percentage of cis and trans isomers is surprisingly similar to those quoted by Young[24] both for experimental (70% hydrogenation of butadiene to cis and trans-but-2-ene), and by thermodynamic calculations of the isomeric content of such an equilibrium mixture.

In an attempt to see if this represented a true equilibrium value, these same minimal catalyst stereomutation conditions were tried on pure trans-undec-4-ene; most surprisingly one mole of hydrogen was absorbed with such rapidity that no accurate estimate of the isomer proportions was possible (case c). These results would certainly seem to indicate not only that the pure trans-isomer undergoes hydrogenation much more rapidly than the cis but also that in mixtures of the two the cis-isomer preferentially occupies the hydrogenation sites and thus inhibits hydrogenation of the trans.

This latter phenomenon would account for the inhibition of hydrogenation of the trans-rich mixture which had been obtained by stereomutation, under conditions in which ready hydrogenation of the pure trans-isomer occurred (cases a, b, c). When sufficient catalyst was used to overcome the poisoning effect of the cis-isomer hydrogenation and isomerisation proceeded side by side. In this case a plot of the hydrogen uptake against percentage trans-isomer (fig. 1) clearly illustrated the competition between cis to trans stereomutation and hydrogenation, and agreed with the above suggestion of more rapid hydrogenation of the trans-isomer. It also suggests the possibility that the cis-isomer is not itself hydrogenated but is first isomerised to the trans and then is reduced.

When the above low catalyst concentration conditions were applied to substantially pure cis-undeca-1, 7-diene (III), prepared by Lindlar reduction of I, hydrogenation of the terminal double bond proceeded fairly rapidly with concurrent substantial stereomutation (79%) of the central double bond (see Experimental).

Since the above work was completed, a number of papers have appeared in the literature. Although most of these are concerned with the mechanisms of hydrogenation of ethylene, acetylene or their deuterated derivatives several are related to the above work. The observed dependence of the relative rates of hydrogenation of cis and trans isomers on catalyst concentration has been further supported by Harwood[33] and Nagy.[34] A significant paper by Japanese workers,[35] previously overlooked, describes the selectivity of palladium catalysts in the hydrogenation of cis and trans - unsaturated fatty acids. They have shown that

(a) cis and trans-isomers are hydrogenated at different rates depending on the catalyst concentration,

(b) the speed of hydrogenation is not a linear function of catalyst concentration,

(c) there is always an amount of catalyst with which the cis-modification is more quickly saturated, and there is also an amount with which the *trans*-isomer is more quickly saturated,

(d) the minimum rate of hydrogenation of the *trans*-isomer always occurs with a smaller catalyst concentration than that of the *cis*. These results collaborate our work.

Bellinzona and Bettinetti[36] have carried out stereomutation studies on *cis*-stilbene and *cis*-cinnamic acid using a wide range of catalysts, supports and solvents. Their results confirm our findings that as the catalyst concentration is decreased the amount of stereomutation increases, and there is no stereomutation in the absence of hydrogen.

CONCLUSION

Our work has shown that, under conditions normally used by organic chemists for the hydrogenation of acetylenes, namely rare metal catalysts on inert supports suspended in inert solvents, the olefinic product contains amounts of *trans*-isomer produced by stereomutation of the initially formed *cis*-olefin. The amount of *trans*-isomer in the final product is dependent on the catalyst concentration and increases with decreasing concentration.

The rate of hydrogenation of *trans*-olefin is much greater than that of its *cis*-isomer, the latter apparently poisoning the catalyst to *trans* hydrogenation. In the hydrogenation of a *cis*-olefin there is concurrent hydrogenation and stereomutation. The rate will therefore depend on the catalyst concentration and will increase if sufficient catalyst is present to offset the poisoning effect of the *cis* on the *trans*-isomer.

The hydrogenation-stereomutation behaviour revealed even by the above relatively crude study is complex and would certainly merit a physico-chemical investigation involving rigidly-standardised quantitative measurements.

EXPERIMENTAL

Undec-4-yne was prepared by the general method for substituted acetylenes.[37] Thus reaction of *n*-propyl iodide (18.7 g., 0.11 mol.) with the disodium salt of oct-1-yne, from the acetylene (11 g., 0.1 mol.) and sodium (2.5 g., 0.11 mol.) in liquid ammonia (100 ml.) gave undec-4-yne as a colourless oil (6.8 g., 45%), b.p. 80-83°/14 mm., n_D^{17} 1.4377.

Cis-*undec*-4-*ene*. Undec-4-yne (4.028 g., 0.026 mol.) in cyclohexane (50 ml.), containing a trace of quinoline, was hydrogenated over Lindlar [38, 39] catalyst (467 mg.). The hydrogen uptake was 600 ml. (Required 593 ml.). The mixture was filtered, washed successively with dilute hydrochloric acid, water and dried over magnesium sulphate. Distillation gave *cis*-undec-4-ene as a colourless oil (3.6 g., 90%), b.p. 80-82°/14 mm., n_D^{21} 1.4297.

Trans-*undec*-4-*ene*. The standard sodium-liquid ammonia procedure for the reduction of the bilaterally substituted acetylenic linkage furnished with undec-4-yne (6.1 g., 0.04 mol.) *trans*-undec-4-ene (5.5 g., 90%), b.p. 105-106°/51 mm., $n_D^{22.5}$ 1.4273.

Stereomutation Experiments.

These experiments were carried out in a conventional hydrogenation apparatus using a flask (250 ml.) fitted with a side arm carrying a serum cap. Cyclohexane was used as solvent and Baker[40] 10% palladium-charcoal as catalyst. Aliquots (5 ml.) were removed at intervals by means of a hypodermic syringe, filtered through celite and the intensity of the *trans*-band at 968 cm^{-1} measured using a Unicam SP 130 priam-grating Infrared spectrophotometer. A standard solution of pure *trans*-undec-4-ene absorbed at $\nu_{max}^{cyclohexane}$ 968 cm^{-1}, $\Delta\nu_{\frac{1}{2}}^{a} = 12$ cm^{-1}, $\varepsilon = 124$.

(i) Substantially pure *cis*-undec-4-ene (490 mg.) in cyclohexane (39 ml.) was shaken in an atmosphere of nitrogen and air with pre-hydrogenated catalyst (43 mg.) for two hours. No stereomutation was observed. A similar result was obtained in an exactly similar experiment using catalyst which had just been used in a hydrogenation (oct-1-yne to oct-1-ene).

(ii) The results in table 1 were obtained using the following conditions.

Case (a) Undec-4-ene (IV) (905 mg.) in cyclohexane (30 ml.) using 10% catalyst (22 mg.)

Case (b) Undec-4-ene (IV) (990 mg.) in cyclohexane (42 ml.) using catalyst (17 mg.)

Case (c) Undec-4-ene (IV) (1036 mg.) in cyclohexane (35 ml.) using catalyst (22 mg.)

Case (d) Undec-4-ene (IV) (1524 mg.) in cyclohexane (32 ml.) using catalyst (128 mg.).

(iii) Hydrogenation of substantially pure <u>cis</u>-undeca-1, 7-diene (III) (1194 mg.) in cyclohexane)35 ml.) using catalyst (27 mg.) resulted in concurrent hydrogenation of the terminal double bond and stereomutation of the central double bond as shown by the following table.

Time (min)	0	17	27	43	72
molar hydrogen absorption	0	0.32	0.5	1.0	1.25
% <u>trans</u> in ethylene product	11	63	79	76	<u>ca</u>. 75

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