FREE RADICAL CYCLIZATIONS

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INTRODUCTION

Interest in free radical cyclizations has increased enormously in the last few years and this Symposium gives a very good opportunity to review this rapidly developing field. An exhaustive review will, however, greatly exceed the time available and I should like to make it quite clear that the selection which had to be made has been directed partly by the need to illustrate general points but also by our own particular interests. It seems convenient to divide this talk into two parts covering two of the main types of reactions which free radicals undergo to generate new bonds:

(i) Addition of free radicals to unsaturated bonds. We shall consider here only double bonds although triple bonds also undergo cyclization reactions.

(ii) Aromatic substitution reactions. We shall restrict ourselves to the formation of new carbon–carbon bonds. We shall not consider here the formation of cyclopropane rings which could be envisioned either as "micro-cyclizations" or homoallylic participations. We will have to omit also the very interesting cyclizations by radical coupling reactions, as well as a few recent very elegant cyclizations of radical anions.

CYCLIZATIONS BY FREE RADICAL ADDITION REACTIONS

Since the discovery of free radicals in solution by Moses Gomberg, which this Symposium commemorates, a very large number of free radical additions to unsaturated linkages have been observed, largely through the work of Morris S. Kharasch and his School. Practically all classes of organic compounds have been added to carbon–carbon double bonds: hydrocarbons, halogen derivatives, aldehydes, alcohols, ethers, amines, ketones, esters, amides; very high yields have sometimes been obtained.

In principle each one of these addition reactions could be used to close a ring. It is surprising that so little use has been made of these possibilities until recently. Some early examples can, however, be found in the literature with 1,5-dienes by addition of hydrogen sulphide[1] of autoxidation[2] (these however are "heterocyclizations").

Free radical formation of alicyclic rings seems to have been mentioned first in the polymerization of 1,6-diolefins[3a] and the addition of various addenda to 1,6-diolefins[3b] (see *Figure 1*).

When we started working in this field, it was quite clear that all possibilities were far from having been explored. We shall see some more recent examples as we go along.

A difficulty at once arises when the particular features of free radical addition reactions are considered. In intermolecular reactions it is common

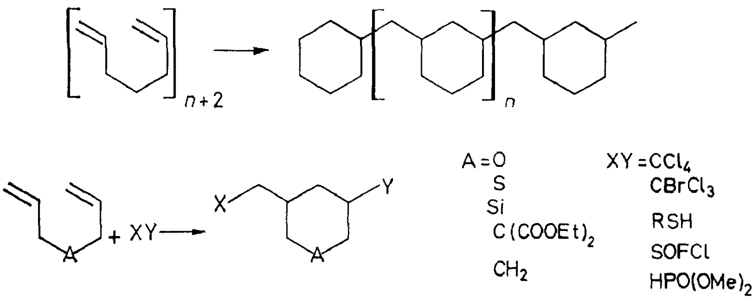


Figure 1

practice to use an (sometimes very large) excess of the addendum in order to minimize telomerization of the olefin. In intramolecular reactions, such as those which are envisioned, the molar ratio of radical to double bond is of course one. For that reason, cyclizations are expected to be less efficient than additions.

On the other hand the fact that the two reacting groups are already in the same molecule is very favourable as regards the entropy of the reaction. For this entropy factor to come into play the two groups must of course be advantageously situated in the starting molecule. This "advantageous situation" is illustrated by the large number of very efficient intramolecular 1,6-hydrogen transfer reactions[8] (see *Figure 2*).

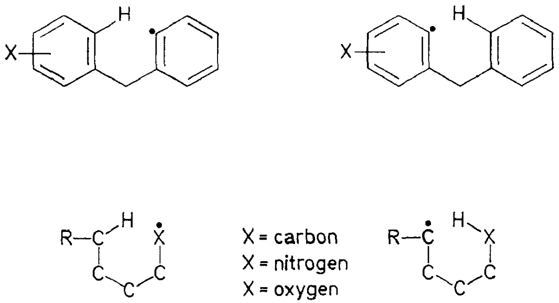
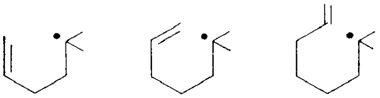


Figure 2

The case with X = nitrogen is observed in the Hoffmann–Loeffler–Freytag reaction[6]. Numerous instances when X = oxygen are known where the free radical is generated by the decomposition of lead(IV) derivatives[7], the photolysis of nitrites[8], and the decomposition of alkyl hypoiodites[9] or hypochlorites[10]. It is quite clear that free radicals will react very efficiently with atoms or bonds situated similarly to the hydrogen in the above scheme.

Consideration of models confirms that poor overlaps of orbitals is experienced between a radical and a $\gamma\delta$ double bond whereas a fairly good overlap occurs both with C_5 and C_6 in a $\gamma\delta$ double bond, and with C_6 in a $\epsilon\zeta$ double bond.



We chose the cyclization of cyanoesters to start our programme. The intermolecular reaction, which had just been described, was very efficient[11]; the starting materials could be readily prepared and the cyclized products, if any, could be easily identified.

As regards experimental conditions it is well known that cyclizations are favoured by dilution, but, as we have seen, we cannot here use an excess of addendum as solvent. We, therefore, had to use another solvent. In order to ensure a convenient temperature for the decomposition of benzoyl peroxide which we intended to use as an initiator we selected boiling cyclohexane which turned out to be better than benzene. It might be said that the cyclization reactions which we have observed are chain reactions (less than half an equivalent of peroxide is needed) but we have reason to believe that the solvent is involved and actually is the hydrogen donor (see *Figure 3*).

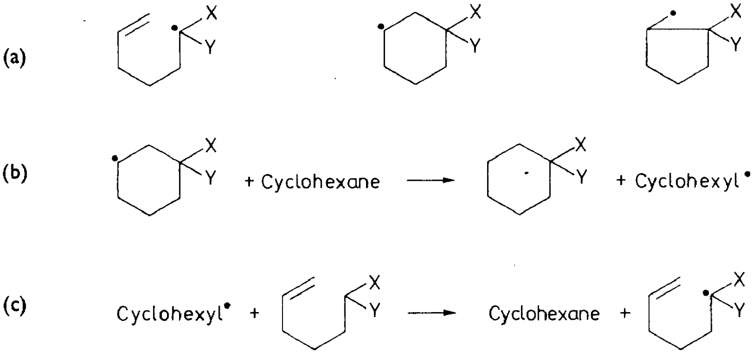


Figure 3

The second step (b) should be a low energy process, which perhaps explains the efficiency of cyclohexane for these reactions.

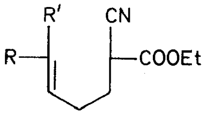
The usual procedure was to add very slowly (during 24–48 h) the starting material together with the peroxide to boiling cyclohexane. With di-*t*-butyl peroxide as initiator we heated the solution in a bomb at *c.* 140°.

Monocyclic compounds

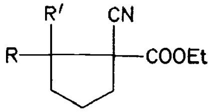
Ethyl 2-cyano-5-hexenoate (I, R = R′ = H) and ethyl 2-cyano-6-methyl-5-heptenoate (I, R = R′ = Me) could not be cyclized but ethyl 2-cyano-5-heptenoate (I, R = Me, R′ = H) gave a 30 per cent yield of ethyl 2-methyl-1-cyanocyclopentane carboxylate (II) (reaction time 168 h)[12a].

The next higher homologue, ethyl *trans*-2-cyano-6-octeneoate (III) (*Figure 4*) gave the cyclohexane derivative (IV)[13] in a yield which could be brought up to 88 per cent (0·2 mole of benzoyl peroxide per mole of starting material; 40 + 40 h; 5 g in 1 l. of cyclohexane). Reduction of the amount of solvent to 100 or 30 ml reduced the yield to 74 and 40 per cent respectively.

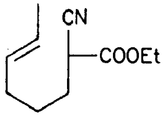
In benzene using the best of the above conditions only 20 per cent of cyclized product was obtained, 40 per cent of the starting material being recovered.



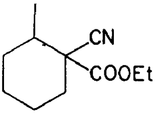
(I)



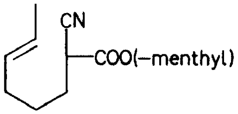
(II)



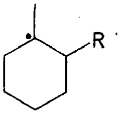
(III)



(IV)



(V)

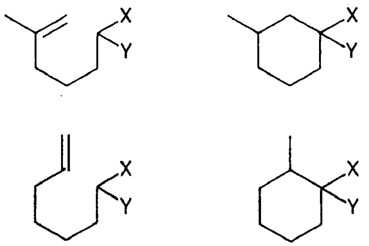


(VI)

Figure 4

Considering the high yield in this cyclization we investigated the possibility of an asymmetric synthesis. The (—)menthyl ester of the same cyano acid (V) was prepared and treated as above. The product (57 per cent) was degraded to the known *trans*-2-methylcyclohexane carboxylic acid (VI, R = COOH) which was found to be optically active and was reduced to *trans*-2-methylcyclohexanemethanol (VI, R = CH_2OH) which had been resolved[14]. The rotation observed shows that the yield of asymmetry achieved is 29–30 per cent[15a].

Before discussing the problem of the size of the ring, let us mention a few cases with isopropenyl chains[15a] which gave only six membered rings as was to be expected (see *Figure 5*).



X = CN
Y = COOEt } 57 %
X = Y = CN 28 %

X = CN
Y = COOEt } 34 %

Figure 5

The homologous 2-cyano-7-octenoate (VII) also gave a cyclohexane derivative although this involved an "anti-Kharasch" addition to the terminal double bond[15b].

A number of other examples of free radical cyclization have been published over the last few years. The simple 5-hexen-1-yl radical has been reported to cyclize to the cyclopentylmethyl or the cyclohexyl radical in the mercury sensitized photolysis of cyclohexane[16] or the pyrolysis of cyclohexane–acetone-d_6 mixtures between 155–400°[17].

Robert C. Lamb[18] and his associates decomposed 6-heptenoyl peroxide in toluene at 77° (see *Figure 6*). They found no acceleration in the decomposition of this peroxide compared with heptanoyl peroxide and obtained,

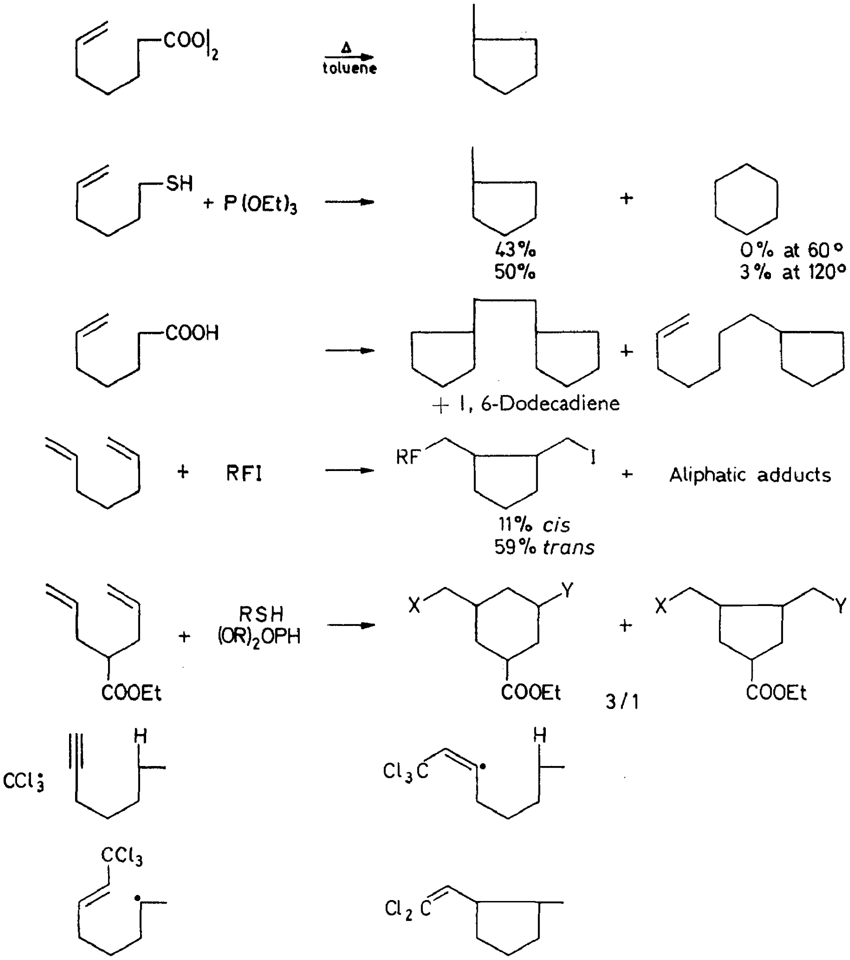


Figure 6

aside from open-chain compounds, methylcyclopentane and a small amount of cyclohexane. Cyclohexane formyl peroxide on the other hand gave only cyclohexane, and cyclopentane acetyl peroxide gave methylcyclopentane (a small amount of cyclohexane was formed by a non-radical path: insensitivity to the addition of hydrogalvinoxyl). They suggested that hexenyl free radical is internally complexed and the ratio of C_5/C_6 rings is determined by the steric requirements of the transition states leading from this radical to the products by hydrogen transfer with the solvent.

Walling and Padwa[19] had explained the remarkable influence of cyclohexene on the hydrogen abstraction reaction of the *t*-butoxy radical by the formation of such a complex.

Shortly thereafter Walling and Pearson[20a] studied the hexenyl radical generated by reduction of 5-hexene-1-thiol by triethyl phosphite. They also found methylcyclopentane with a few percent of cyclohexane. Garwood, Scott and Weedon[20b] observed the formation of cyclopentane compounds in the electrolysis of 6-heptenoic acid.

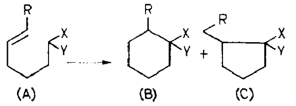
Brace[21a] has studied the addition of 1-iodoperfluoropropane to 1,6-heptadiene and again cyclization gives only cyclopentane derivatives. The suggested explanation is the difference in efficiency of the transfer steps involved.

Cadogan, Hey and Ong[21b] have added thiols or dialkyl phosphites to ethyl diallylacetate and observed both cyclohexane and cyclopentane ring formation in a ratio of 3/1. Very recently[12b] a remarkable cyclization to a dichlorovinyl cyclopentane derivative has been reported.

The striking difference in the size of the rings formed in the cyclization of the primary radicals to cyclopentanes compared to the formation of cyclohexane derivatives from highly resonance stabilized α-cyano ester radicals made it desirable to investigate this point more closely.

We therefore prepared a series of related compounds of the general type shown in *Table 1* and submitted them to free radical cyclization conditions. The results show that the α-cyano esters are extreme cases; almost all others with the understandable exception of the substituted malononitriles led to mixtures of cyclohexane and cyclopentane compounds, with the latter

Table 1. Compounds of the general type A submitted for free radical cyclization conditions to obtain compounds B and C

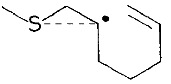


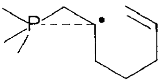
X	Y	R	*Total cyclized* (%)	2 (C_6) (%)	*Isomers*	3 (C_5) (%)	*Isomers*	Peroxide (a) = benzoyl (b) = (t-BuO)$_2$
CN	CO_2Et	H	58	84		16		(a)
		CH_3	90	100		0		(a, b)
CN	CN	H	70	80		20		(a)
		CH_3	50	100		0		(a)
CO_2Et	CO_2Et	H	55	40		60		(a, b)
		CH_3	26	65		35		(a)
$COCH_3$	CO_2Et	H	33	50		50		(a, b)
		CH_3	33	50		50		(a, b)
Cl	CO_2Et	H	15	11		89		(a)
H	CN	H	22	0		100	65% *trans* 35% *cis*	(b)
		CH_3	19	0		100	66% *trans* 34% *cis*	(b)
H	CO_2Et	H	30	44		56	60% *trans* 40% *cis*	(b)
		CH_3	25	0		100	75% *trans* 25% *cis*	(b)
H	$COCH_3$	H	13	28		72	70% *trans* 30% *cis*	(b)
		CH_3	25	36	90% *trans* 10% *cis*	64	70% *trans* 30% *cis*	(b)
H	=O	H	41	100		0		(a)
		CH_3	54	100		0		(a)

becoming the main compounds in the case of mono esters, nitriles or ketones[22].

The more substituted radicals seem to give a larger proportion of C_6 rings but comparison of the diester or keto ester with the chloroester shows that bulk (influencing sterically the stabilities of the two transition states) is not the only factor; rather, stability of the first radical seems determining since with two resonance stabilizing substituents on the radical carbon, large to fair proportions of cyclohexane derivatives are formed. Total yields are also higher which is reasonable since more time is available for the double bond to "come around" and participate. A similar phenomenon has been observed in the participation of a double bond with a carbonium ion[23].

Cadogan, Hey and Ong[24] have recently obtained cyclohexane derivatives from ethylenic, cyano-keto or diesters using conditions similar to ours. It is remarkable that in the cases mentioned above[21b], where substantial C_6 ring formation was observed, the radicals involved were stabilized by beta-sulphur or phosphorus atoms.





The simple aldehydes, 5-hexenal and 5-heptenal, give only cyclohexane derivatives. A few more complex cases had been described by Dulou and his associates[25] including formation of camphor or apocamphor from α-camphenilaldehyde or apo-α-camphenilaldehyde; of menthone and isomenthone from citronellal and piperitone and from citral with acetyl peroxide without solvent or in hexane. Here C_6 rings are formed in preference to C_7 ones.

It does not seem possible with the available evidence to give a completely satisfactory explanation of these results. It looks as if very reactive free radicals reacted with the more immediately available end of the double bond without much regard to the comparative stability of the end products.

With a less reactive free radical one might argue that the transition states involved resemble the products more closely.

The cyclohexane derivatives both in the disubstituted cases and the aldehydes should be considered as more stable than their C_5 ring isomers (eclipses of substituents and strain of the ring) (see *Figure 7*).

Some more recent findings however show that this is too simple a view: the simple cyanoester was irradiated in acetone–cyclohexane solution (Elad[26] has obtained very good results with this technique in intermolecular additions) so that the temperature could be lowered. At 80° the cyclization proceeded very much as with peroxide initiation. At lower temperature however the results are shown in *Table 2*. Cyclopentane ring formation is favoured.

The initiator and the solvent also seem to have an influence. It is hoped that with this technique more information will be obtained that will help to understand the interplay of the various factors. (See the note added in proof on page 182.)

It is interesting to compare the cyclization of these radicals to that of

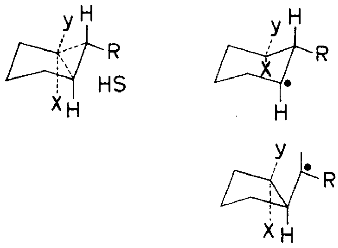
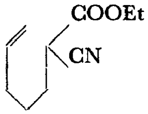


Figure 7

Table 2. Cyclization of 

Solvent	*Temperature* (°C)	*Initiator*		C$_6$† (%)	C$_5$† (%)
Methylcyclohexane–isopentane (2:1)	−70°	hν	Acetone	20	80
Methylcyclohexane isopentane (2:1)	22°	hν	Acetone	50	50
Cyclohexane	35°	hν	Acetone	61	39
Cyclohexane	65°	hν	Acetone	74	26
Decalin	150°	hν	Benzophenone	89	11
Decalin	30°	hν	Benzophenone	70	30
Decalin	−70°	hν	Benzophenone	50	50
Cyclohexane	77°	hν	Benzophenone	63	37
Cyclohexane	81°	$(PhCO_2)_2$		86	14
Cyclohexane	140°	$(t\text{-}BuO)_2$		86	14

† The results are within ±3 per cent range.

related ions; hexenyl cation gives cyclohexanol and thenylhexenyl anion gives phenylmethylcyclopentane[28] (see *Figure 8*).

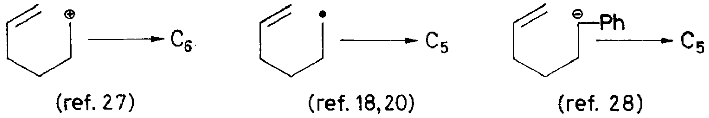


Figure 8

Polycyclic compounds

In order to synthesize bicyclic compounds it is convenient to start with monocyclic olefins (*Figure 9*). The isomeric ethyl cyclopentenylpropylcyanoacetates (VIII) were cyclized to *cis* hydrindane derivatives[30]. Ethyl cyclohexenylpropylcyanoacetate (IX) was cyclized to a saturated compound which was degraded to *trans,trans* cyclohexane carboxylic acid[31].

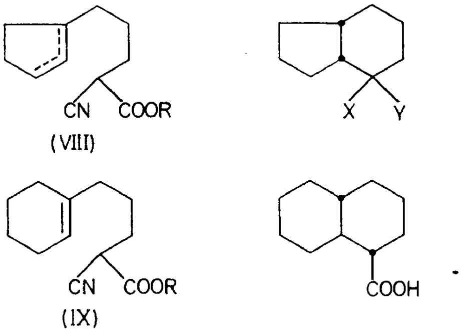


Figure 9

The *trans* stereochemistry of the decalin system formed meant that the *cis* decalyl free radical first formed epimerized to the more stable isomer before the hydrogen transfer step. It has been shown recently by Bartlett that *cis* decalyl free radicals actually epimerize extremely rapidly[52].

The bicyclization of diene derivatives was of interest since it could be related to the biosynthetic cyclization of polyolefines of the squalene type. Free radical oxidizing cyclization of squalene itself has been attempted[32].

Ethyl α-cyano-6,10-undecadienoate (X) was cyclized to a decalin system which was degraded to *trans,trans* α-decalol[33a]. A hydrophenanthrene derivative could also be prepared by double cyclization[33b] (see *Figure 10*).

A few heterocyclic rings have been obtained in related reactions. Lamb[34] and his associates have decomposed β-allyloxypropionyl peroxide (XI) in

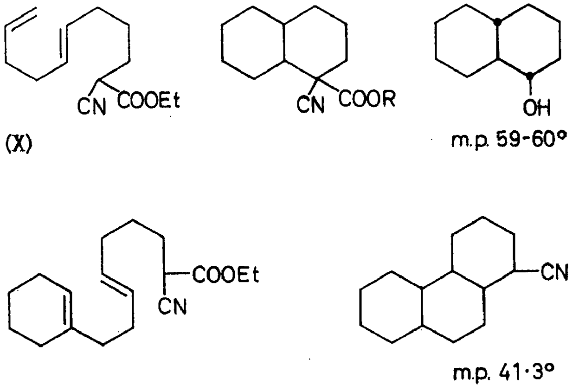


Figure 10

toluene and found that the cyclization gave exclusively 3-methyltetrahydrofuran (no six membered ring was formed). A few ethylenic amines have been cyclized although in low yield.

The role of the solvent was apparent in an attempt to cyclize α-bromo-6-heptenonitrile (XII). The cyclized products isolated were *cis* and *trans*-2-methylcyclopentane nitrile and a small amount of cyclohexane nitrile;

bromocyclohexane was formed in 63 per cent yield[35]. This showed that hydrogen transfer took place with the solvent and bromine was removed from a new molecule by the cyclohexyl radical. An aliphatic saturated α-bromonitrile was found to exchange bromine readily with the solvent under the same conditions but heptene nitrile itself cyclized very much less efficiently (see *Figure 11*).

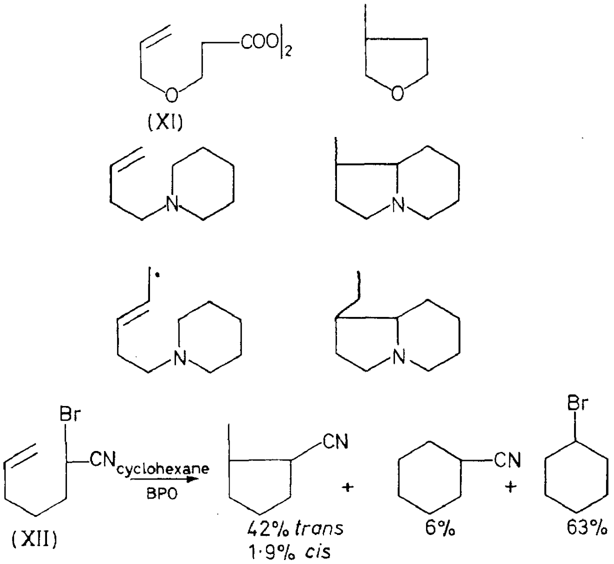
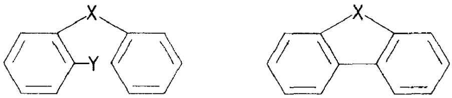


Figure 11

CYCLIZATIONS BY FREE RADICAL AROMATIC SUBSTITUTION

The second part of this talk will be devoted to cyclizations in which the key step is an aromatic substitution. Among these are very early instances which in fact were discovered before their free radical nature was recognized. These comprise the group of intramolecular aromatic arylation reactions of which a well known example is the Pschorr phenanthrene synthesis[37] (see *Figure 12*).



X = CH_2	Y = NH_2
CO	NH_2
CH=CH *cis*	NH_2 or Br
CH_2-CH_2	NH_2
O, NR, S, SO_2	NH_2

Figure 12

Quite recently[38] an efficient cyclization of *cis*-*o*-bromostilbene to phenanthrene with a Grignard reagent and cobaltous chloride has been reported.

Phenylbutyl radicals have been shown to cyclize when the solvent is not too good a chain transfer agent. These and related radicals were produced from phenyl pentyl derivatives by decarbonylation of the aldehydes[39], decomposition of the acyl peroxide[40, 41], electrolysis of the acid[42], or treatment of the acid with lead tetracetate[43] (see *Figure 13*).

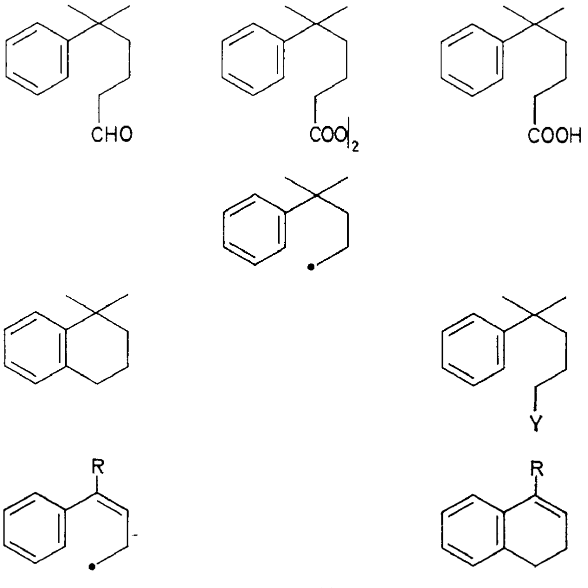


Figure 13

The pyrolysis of a suitable mercury derivative led to cyclization with formation of a substituted tetralin[44a]. Tetralin itself has been obtained in the pyrolysis of the vinyl ether of phenylcyclopropyl carbinol[44b]. In a similar way aryl propionyl and butyroyl radicals have been cyclized to indanones and tetralones[45]. Quite recently a similar cyclization to a fluorenone has been reported by Huang[46] (see *Figure 14*).

We have been engaged for some time in related cyclizations. Ethyl 5-phenyl-2-cyanovalerate could not be cyclized with benzoyl or di-*t*-butyl peroxide. So it appeared that these highly resonance stabilized radicals would not attack an aromatic ring as easily as a double bond. We then turned to more reactive free radicals such as those which are intermediates in addition reactions. With 1-phenyl-4-pentene (XIII), addition of XY should lead to a radical suitably placed with regard to the ring (see *Figure 15*). But of course the desired cyclization leading to (XIV) would be in competition with chain transfer leading to simple addition (XV). With too efficient transfer agents, this is the preferred pathway as reported by Martin and Gleicher[47], working with $CBrCl_3$.

The addition of ethyl cyanoacetate (10/1 molar proportion) to phenylpentene gave different results when benzoyl peroxide or di-*t*-butyl peroxide

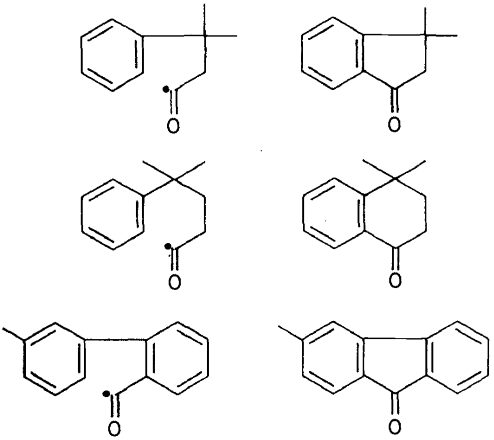


Figure 14

were used as initiators[48]. It can be seen from *Table 3* that one mole of benzoyl peroxide is necessary to convert all the olefin, that the yield of total 1:1 products is fairly constant but that the ratio of cyclized to non-cyclized products increases from 0·59 (with 0·15 mole of peroxide) to 1·32 (with 1 mole of peroxide).

When the reaction mixture is diluted with benzene (in the hope of favouring the cyclization) the total yield of 1:1 products decreases and the ratio of cyclized to non-cyclized products increases (0·72 and 2·5).

With cyclohexane as solvent fair yields of 1:1 products with high proportions of cyclized product were obtained with essentially complete conversion of the olefin.

With di-*t*-butylperoxide, in excess cyanoacetate, only the addition product could be obtained. With benzene as diluent a few per cent of cyclized product was formed. Only with equimolecular amounts of cyanoacetate and olefin could a fair proportion of cyclization be observed (cyclized/non-cyclized = 0·7) (*Table 4*). We were thus encouraged to attempt

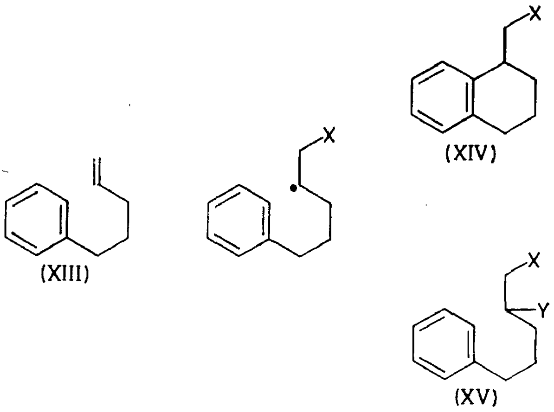


Figure 15

Table 3. Olefin conversion, formation of 1 :1, cyclized and non-cyclized products from phenylpentene and ethyl cyanoacetate using benzoyl peroxide as initiator

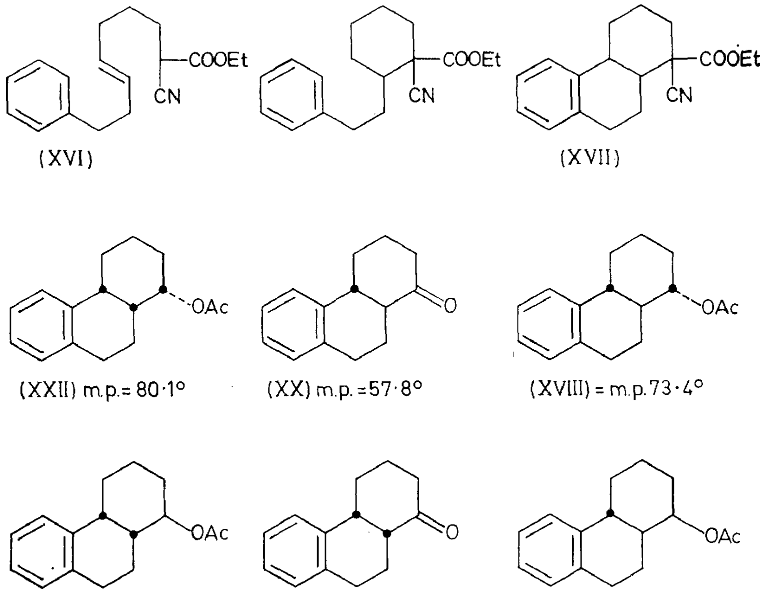
Reactants (mole)		*Initiator* (mole) *Benzoyl peroxide*	*Solvent* (mole)	*Olefin conversion* (%)	1:1 *Products* (%)	*Non-cyclized products* (%)	*Cyclized products* (%)	*Ratio of cyclized to non-cyclized products*	*Ratio of per cent cyclized to olefin*	*Ratio of per cent cyclized to peroxide*
Phenyl-pentene	*Ethyl-cyanoacetate*									
1	10	0·15		49	45	63	37	0·59	16	55
1	10	0·30		89	37	50	50	1	18·5	56·5
1	10	0·70		87	41·5	44	56	1·27	23	29
1	10	1		100	43	43	57	1·32	24·5	25
1	10	1·2		100	42	45	55	1·22	22·5	17
1	10	1·5		100	30	40	60	1·50	18	12
1	10	0·15	75 C_6H_6	38	27	58	42	0·72	11·5	31
1	10	1	75 C_6H_6	57	34	29	71	2·45	24	14
1	1	0·15	75 C_6H_6			50	50	1		
1	1	1	75 C_6H_6	28	15·5	50	50	1	7·7	2
1	10	1	75 C_6H_{12}	100	51	32	68	2·12	35	35
1	1	1	75 C_6H_{12}	85	26	23	77	3·35	20	17

Table 4. Olefin conversion, formation of 1 :1, cyclized and non-cyclized products from phenylpentene and ethyl cyanoacetate using di-*t*-butyl peroxide as initiator

Reactants (mole)		*Initiator* (mole) *Di-t-butyl peroxide*	*Solvent* (mole)	*Olefin conversion* (%)	1 :1 *Products* (%)	*Non-cyclized products* (%)	*Cyclized products* (%)	*Ratio of cyclized to non-cyclized products*	*Ratio of per cent cyclized to olefin*	*Ratio of per cent cyclized to peroxide*
Phenyl-pentene	*Ethyl cyanoacetate*									
1	10	0·15		100	60	>99	<1			
1	10	1		100	45	>99	<1			
1	10	0·15	75 C_6H_6	78	57	99	1	0·01	0·5	3·9
1	10	1	75 C_6H_6	100	45	96	4	0·04	1·5	1·5
1	1	0·15	75 C_6H_6	81	18	65	35	0·55	6·5	33
1	1	1	75 C_6H_6	63	20	59	41	0·7	8·5	5
1	10	1	75 C_6H_{12}	100	34	>99	<1			
1	1	1	75 C_6H_{12}	100	8·5	65	35	0·55	3	3

the synthesis of a tricyclic compound in a reaction that would incorporate both an addition to a double bond and an aromatic substitution.

Ethyl 2-cyano-9-phenyl-6-nonenoate (XVI) was then prepared by standard methods. The central double bond resulting from opening of a 3-chlorotetrahydropyran derivative with sodium should have the *trans* configuration[49]. In benzene with BPO or DBPO, no satisfactory results were obtained. After treatment with BPO in cyclohexane, however, distillation of the reaction products gave an oil which was largely crystalline. Analysis, i.r. and n.m.r. examinations of this crystalline product indicated that it was the expected tricyclic compound (XVII) (see *Figure 16*). The oily fraction contained more of this compound and the product of monocyclization which could be degraded to 2-phenethylcyclohexane carboxylic acid, identical with an authentic sample. The conversion is essentially complete, the yields are 4 per cent for the simple addition and 42 per cent for the bicyclization (calculated on the olefin; 34 per cent calculated on the peroxide). DBPO gives a somewhat lower total yield (27 per cent) and a smaller ratio of tricyclic/bicyclic compound (70/30). The structure of the tricyclic compound was confirmed by hydrolysis and by decarboxylation to the monoacid followed by degradation either with lead tetracetate or by the Baeyer–Villiger reaction on the methyl ketone. The acetate formed was hydrolysed and the alcohol oxidized to a ketone m.p. 57–58° (XX) which could be epimerized with acid or base to an isomeric ketone m.p. 73–74° (XXI). This last ketone was identical with the product of Friedel–Crafts cyclization of 8-phenyl-5-octenoyl chloride according to Ansell and associates[50]. When



(XVI) (XVII)

(XXII) m.p.= 80·1° (XX) m.p. =57·8° (XVIII) = m.p.73·4°

(XXIII) oil (XXI) m.p.= 73·4° (XIX) m.p. = 86·7°

Figure 16

repeating their experiment with milder isolation conditions, we obtained the less stable ketone (XX). The *trans* configuration had been considered for the more stable ketone. However, a number of cases[51] have been reported when *cis* octahydrophenanthrones are actually more stable than their *trans* isomers, even without the angular methyl group.

It was important to compare this stereochemistry with that of the free radical cyclization of the diolefin above and also to ascertain the value of this method in the synthesis of other products. We obtained information on this point by n.m.r. investigation[55] of the four alcohols (acetates) which could be obtained by appropriate reductions of the two ketones with lithium aluminium hydride or isobornyl oxyaluminium dichloride[53].

The coupling constants of the —CHOAc protons led to the conclusion that the less stable ketone has the *trans* configuration.

Note added in proof

The cyclization step had been shown to be irreversible in the unsubstituted case. Remarks by Professors de Tar and Bartlett at the Symposium incited us to check on this point in the case of substituted radicals[54]. It has indeed been found that in some cases cyclopentyl methyl free radicals can lead to cyclohexane compounds. Together with the lower activation energy found for cyclopentane formation this means that C_5 formation is the kinetically favoured process and that in some cases equilibration can lead to varying amounts of C_6 derivatives.

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References

[1] R. F. Naylor. *J. Chem. Soc.* 1532 (1947).
[2] J. L. Bolland and H. Hughes. *J. Chem. Soc.* 492 (1949).
[3a] G. B. Butler and R. J. Angelo. *J. Am. Chem. Soc.* **79**, 3128 (1957); C. S. Marvel and R. D. West. *J. Am. Chem. Soc.* **79**, 5771 (1957); C. S. Marvel and J. K. Still. *J. Am. Chem. Soc.* **80**, 1740 (1958).
[b] W. S. Friedlander. *A.C.S. Meeting Abstracts* **133**, 18 N (1958).
[4] De Los De Tar and D. J. Relya. *J. Am. Chem. Soc.* **76**, 1202 (1954); **78**, 4302 (1956).
[5] C. A. Grob and H. Kammuller. *Helv. Chim. Acta* **40**, 2139 (1957).
[6] M. E. Wolff. *Chem. Rev.* **63**, 55 (1963).
[7] G. Cainelli, M. Lj. Mihailovic, D. Arigoni and O. Jelger. *Helv. Chem. Acta* **42**, 1124 (1959); K. Heusler and J. Kalvoda. *Angew. Chem.* **76**, 518 (1964).
[8] D. H. R. Barton, J. M. Beaton, L. E. Geller, and M. M. Pechet. *J. Am. Chem. Soc.* 2640 (1960).
[9] C. Meystre, K. Heusler, J. Kalvoda, P. Wieland, G. Anner, and A. Wettstein. *Experientia* **17**, 475 (1961).
[10] C. Walling and A. Padwa. *J. Am. Chem. Soc.* **85**, 1597 (1963).
[11] H. Kosche and O. Rosenthal. *British Pat.* 792 486 to the Henkel Co. *Chem. Abstr.* **52**, 19957 d (1958), *German Pat.* 1 011 873. *Chem. Abstr.* **53**, 15989 (1959).
[12a] M. Julia and F. Le Goffic. *C.R. Acad. Sci.* **255**, 539 (1962); *Bull. Soc. Chim. Fr.* 1550 (1965).
[b] El Ahmadi, I. Heiba, and R. M. Dessau. *J. Am. Chem. Soc.* **88**, 1589 (1966).
[13] M. Julia, J. M. Surzur, and L. Katz. *C.R. Acad. Sci.* **251**, 1030 (1960); *Bull. Soc. Chim. Fr.* 1109 (1964).
[14] A. K. Macbeth, J. A. Mills, and D. H. Simmonds. *J. Chem. Soc.* 1111 (1949).
[15a] M. Maumy. Thèse, Paris (1965).
[b] L. Katz. Thèse, Paris (1962).

[16] S. Arai, S. Sato, and S. Shida. *J. Chem. Phys.* **33**, 1277 (1960).
[17] A. R. Gordon and S. R. Smith. *J. Phys. Chem.* **66**, 521 (1962).
[18] R. C. Lamb, P. W. Ayers, and M. K. Toney. *J. Am. Chem. Soc.* **85**, 3483 (1963).
[19] C. Walling and A. Padwa. *J. Am. Chem. Soc.* **84**, 2845 (1962); **85**, 1593 (1963).
[20a] C. Walling and M. S. Pearson. *J. Am. Chem. Soc.* **86**, 2262 (1964).
[b] R. F. Garwood, C. J. Scott, and B. C. L. Weedon. *Chem. Comm.* 14 (1965).
[21a] N. O. Brace. *J. Am. Chem. Soc.* **86**, 523 (1964).
[b] J. I. G. Cadogan, D. H. Hey, and S. H. Ong. *Chem. & Ind.* 753 (1964).
[22] M. Julia and M. Maumy. *Bull. Soc. Chim.* 434 (1966).
[23] W. S. Johnson, W. H. Lunn, and K. Fitzi. *J. Am. Chem. Soc.* **86**, 1972 (1964).
[24] J. I. G. Cadogan, D. H. Hey, and S. H. Ong. *J. Chem. Soc.* 1932 (1965).
[25] R. Dulou, Y. Chretien-Bessiere, and H. Desalbres. *C.R. Acad. Sci.* **258**, 603 (1964); J. P. Montheard. *C.R. Acad. Sci.* **260**, 577 (1965).
[26] D. Elad and J. Rokach. *J. Org. Chem.* **29**, 1855 (1964); *J. Chem. Soc.* 800 (1965); *J. Org. Chem.* **30**, 3361 (1965).
[27] P. D. Bartlett, W. D. Closson, and T. J. Cogdell. *J. Am. Chem. Soc.* **87**, 1308 (1965), and earlier references cited therein.
[28] H. Pines, N. C. Sih, and E. Lewicki. *J. Org. Chem.* **30**, 1457 (1965).
[29] C. Walling. *Free radicals in solution* J. Wiley and Sons, New York, 1957, p. 628.
[30] M. Julia and F. Le Goffic. *Bull. Soc. Chim.* 1555 (1965).
[31] M. Julia, J. M. Surzur, and L. Katz. *C.R. Acad. Sci.* **251**, 1030 (1960); M. Julia, J. M. Surzur, L. Katz, and F. Le Goffic. *Bull. Soc. Chim. Fr.* 1116 (1964).
[32] R. Breslow, E. Barrett, and E. Mohacsio. *Tetrahedron Letters* 1208 (1962).
[33a] M. Julia, F. Le Goffic, and L. Katz. *Bull. Soc. Chim. Fr.* 1122 (1964).
[b] M. Julia and F. Le Goffic. *Bull. Soc. Chim. Fr.* 1129 (1964).
[34] R. C. Lamb, J. G. Pacifici, and P. W. Ayers. *J. Org. Chem.* **30**, 3099 (1965).
[35] M. Maumy. Personal communication.
[36] M. Julia and Ph. Dostert. *C.R. Acad. Sci.* **259**, 2872 (1964).
[37] De Los F. De Tar. *Org. Reactions*, Vol. 9, 409 (1957).
[38] M. Tiecco. *Chem. Comm.* 555 (1965).
[39] S. Winstein, R. Heck, S. Lapporte, and R. Baird. *Experientia* **12**, 138 (1958).
[40] De Los F. De Tar and C. Weiss. *J. Am. Chem. Soc.* **78**, 4296 (1956).
[41] J. K. Kochi and R. D. Gilliom. *J. Am. Chem. Soc.* **86**, 5251 (1964).
[42] P. J. Bunyan and D. H. Hey. *J. Chem. Soc.* 1360 (1962).
[43] D. I. Davies and C. Waring. *Chem. Comm.* 263 (1965).
[44a] A. Maercker and J. D. Roberts. *J. Am. Chem. Soc.* **88**, 1751 (1966).
[b] S. Julia and D. Obitz, Private communication.
[45] W. H. Urry, D. J. Trecker, and H. D. Hartzler. *J. Org. Chem.* **29**, 1663 (1964).
[46] R. L. Huang and H. H. Lee. *J. Chem. Soc. C*, 929 (1966).
[47] M. M. Martin and G. J. Gleicher. *J. Am. Chem. Soc.* **86**, 233, 238 (1964).
[48] M. Julia and J. C. Chottard. *C.R. Acad. Sci.* **259**, 2653 (1964).
[49] O. Riobe. *Ann. chim. Paris* **4**, (12) 593 (1949); L. Crombie and S. H. Harper. *J. Chem. Soc.* 1707 (1950); C. L. Stevens, B. Cross, and T. Toda. *J. Org. Chem.* **28**, 1283 (1963).
[50a] M. F. Ansell and S. S. Brown. *J. Chem. Soc.* 3958 (1958).
[b] M. F. Ansell and J. W. Ducker. *J. Chem. Soc.* 206 (1961).
[51a] D. Arigoni, J. Kalvoda, H. Heusser, O. Jeger, and L. Ruzicka. *Helv. Chim. Acta* **38**, 1857 (1955); see also ref. 50b footnote p. 206.
[b] H. Christol and Y. Pietrasanta, Private communication.
[52] P. D. Bartlett, R. E. Pincock, J. H. Rolston, W. G. Schindel, and L. Singer. *J. Am. Chem. Soc.* **87**, 2590 (1965).
[53] E. Eliel and D. Nasipuri. *J. Org. Chem.* **31**, 3809 (1965).
[54] M. Julia, M. Maomy and L. Mion *Bull. Soc. Chim. Fr.* 2641 (1967).
[55] M. Julia, J. C. Chottard and J. J. Basselier. *Bull. Soc. Chim. Fr.* 3037 (1966).