964 (1963).
240. V. A. Nazarenko and L. I. Vinarova, Zhur. Anal. Khim., 18, 1217 (1963).
241. V. A. Nazarenko and E. N. Poluektova, Zhur. Anal. Khim., 19, 1459 (1964).
242. V. A. Nazarenko and G. V. Flyantikova, Zhur. Neorg. Khim., 7, 2335 (1962) [Russ. J. Inorg. Chem., 1210 (1962)].
243. T. Kanno, Sci. Reports Res. Inst., Tôhoku Univ., A11, 145 (1959).
244. L. Hörhammer and R. Hänsel, Arch. Pharm., 286/58, 425 (1953).
245. L Hörhammer, R. Hänsel, and W. Hieber, Naturwiss., 41, 529 (1954).
246. L. Hörhammer, R. Hänsel, and W. Hieber, Z. analyt. Chem., 148, 251 (1955).
247. V. A. Nazarenko and G. V. Flyantikova, Zhur. Anal. Khim., 18, 172 (1963).
248. H. Sano, Bull. Chem. Soc. Japan, 33, 286 (1960).
249. G. T. Morgan and H. D. K. Drew, J. Chem. Soc., 125, 1261 (1924).
250. O. B. Scaar and F. J. Langmyhr, Analyt. Chim. Acta, 21, 370 (1959).
251. V. A. Nazarenko, N. V. Lebedeva, and L. I. Vinarova, Zhur. Anal. Khim., 19, 87 (1964).
252. V. I. Davydov and N. P. Diev, Zhur. Prikl. Khim., 32, 441 (1959).
253. R. Schwarz and H. Giese, Ber., 63, 778 (1930).
254. R. E. D. Clark, Analyst, 82, 760 (1957).
255. B. N. Ivanov-Emin and V. M. Kostrikin, Zhur. Obshch. Khim., 17, 1253 (1947).
256. G. L. Roy, A. L. Laferriere, and J. O. Edwards, J. Inorg. Nuclear Chem., 4, 106 (1957).
257. V. I. Kuznetsov, Trudy Kom. Anal. Khim. Akad. Nauk SSSR, 11, 35 (1960).
258. H. G. Lander, J. Inorg. Nuclear Chem., 26, 59 (1964).
259. E. R. Clark, J. Inorg. Nuclear Chem., 25, 353 (1963).

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THE DIELS–ALDER REACTION WITH MOLECULAR OXYGEN AS DIENOPHILE

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I. INTRODUCTION

The present review surveys the reactions of conjugated dienes with molecular oxygen to form peroxides.

It has been established that transannular epidioxides are produced by the photosensitised oxidation of alicyclic, aromatic, and heterocyclic homoannular 1,3-dienes. Such dienes undergo the Diels–Alder reaction with maleic anhydride and other dienophiles. Therefore the photooxidation of homoannular 1,3-dienes to transannular epidioxides can be regarded as a photochemical Diels–Alder reaction in which oxygen acts as dienophile.

It has recently been found that homoannular 1,3-dienes are oxidised to transannular epidioxides by molecular oxygen in an excited singlet state. This must be regarded as a diene synthesis with singlet oxygen. It is probable that excited singlet oxygen is the active intermediate also in photosensitised oxidations with molecular oxygen.

The ability of homoannular 1,3-dienes to form transannular epidioxides at low temperatures, and also the ease with which some of the latter rearrange into more stable oxygen compounds or break down again with the liberation of oxygen, suggest that some biological oxidation processes may involve the intermediate formation of transannular epidioxides. This hypothesis has recently been confirmed experimentally.

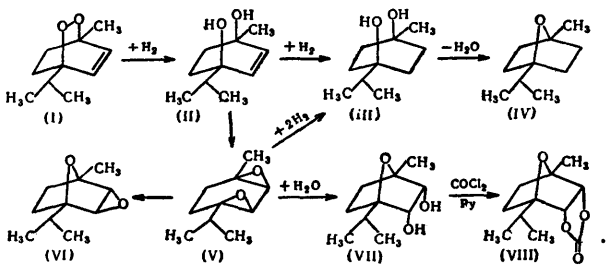
The paper covers the literature published up to 1st March 1965.

II. REACTION OF MOLECULAR OXYGEN WITH ACYCLIC AND ALICYCLIC 1,3-DIENES

1. Ascaridole

In 1908 Gütig[1] isolated an oily substance, having the composition $C_{10}H_{16}O_2$ and boiling at 80–84° (4–5 mm), from chenopodium oil (the essential oil of a species of wormwood, *Chenopodium ambrosioides* var. *anthelminticum*), which possesses an anthelmintic (vermifugal) action. This substance, which is the active principle of chenopodium oil, was termed *ascaridole*. In 1912 Wallach[2,3] established that ascaridole was 1,4-epidioxy-*p*-menth-2-ene (I): catalytic hydrogenation with colloidal palladium gave the previously unknown *p*-menthane-*cis*-1,4-diol (III), dehydration of which with oxalic acid yielded the known 1,4-epoxy-*p*-menthane (IV).

It must be noted that at that time ascaridole was the only known organic compound having a transannular epidioxide structure.



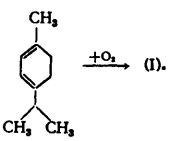
Study of the chemical properties of ascaridole gave interesting results. Catalytic hydrogenation with platinum

oxide[4] or with Raney nickel[5] yielded the diol (III). Reduction with lithium tetrahydroaluminate[6] or with a potassium–sodium alloy in ether[5] produced *p*-menth-2-ene-1,4-diol (II). This unsaturated glycol (II) was also obtained by the catalytic reduction of ascaridole with relatively inactive palladium[4] or nickel[5] catalysts. When heated to 130–150° ascaridole decomposes explosively[2,3]. Nelson[7] found that when heated in *p*-cymene at 150°, ascaridole isomerises to a diepoxy-*p*-menthane. It was found later[6,8] that the thermal isomerisation of ascaridole is more conveniently carried out in boiling xylene, and Schenck[5] showed that ascaridole is converted into this diepoxide by the action of ultraviolet radiation. Nelson[7] assumed that, on being heated, ascaridole is first converted into an unstable isomer, 1,2:3,4-diepoxy-*p*-menthane (V), which then rearranges to the stable isomer, 1,4:2,3-diepoxy-*p*-menthane (VI). In the presence of dilute sulphuric acid, the diepoxide adds on a molecule of water to form 1,4-epoxy-*p*-menthane-2,3-diol (VII). The cyclic carbonate (VIII) has been obtained[9] by the action of carbonyl chloride and pyridine on (VII). Matic and Sutton[6] determined the structure of the thermal isomerisation product of ascaridole by reducing it with lithium tetrahydroaluminate, and isolated the compound (III) and a triol $C_{10}H_{20}O_3$ from the reaction products. The formation of (III) proved the presence of the 1,2:3,4-diepoxide (V) in the product of isomerisation. The triol $C_{10}H_{20}O_3$ could have been formed by reduction of the 1,4:2,3-diepoxide (VI) to 1,4-epoxy-*p*-menthan-2(or 3)-ol, followed by hydration of the latter to *p*-menthane-1,2(or 3),4-triol. It follows from these results that the product of the thermal isomerisation of ascaridole is probably a mixture of the diepoxides (V) and (VI)†. It must be noted that the configuration of 1,4-epoxy-*p*-menthane-2,3-diol (VII) has not been rigorously proved.

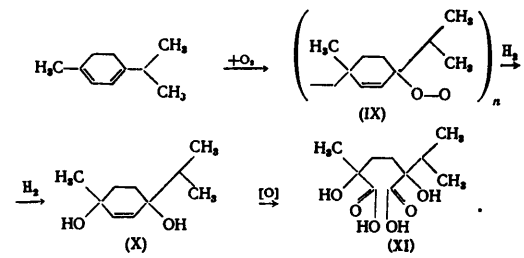
Ascaridole is used in medicine for the treatment of intestinal helminthiases in both adults and children. Chemists use ascaridole as an initiator for radical reactions.

2. Autoxidation of Acyclic and Alicyclic 1,3-Dienes

Ascaridole (I) can be regarded as an internal peroxide of *p*-mentha-1,3-diene. In 1933 Bodendorf[4] put forward the hypothesis that autoxidation of the latter compound involves the addition of oxygen to the conjugated system of double bonds at the 1,4 positions to form ascaridole:



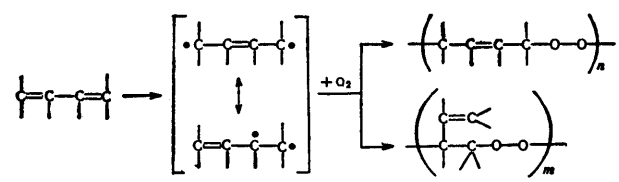
However, experiments undertaken to test this hypothesis showed that molecular oxygen reacts with *p*-mentha-2,3-diene to form, not ascaridole, but an unsaturated polymeric peroxide of low molecular weight. Bodendorf reduced the polyperoxide catalytically, and oxidised the reduction product with potassium permanganate. From the oxidation products he isolated 2,5-dihydroxy-2-isopropyl-5-methyladipic acid (XI). Hence it followed that in the autoxidation of *p*-mentha-1,3-diene the oxygen added on at the 1,4 positions to form the unsaturated polymeric peroxide (IX), catalytic reduction of which yielded the unsaturated glycol (X), and this was oxidised to the dicarboxylic acid (XI):



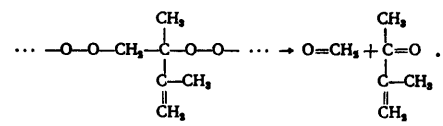
Bodendorf also found that only polymeric peroxides were formed in the oxidation of other diene hydrocarbons (*p*-mentha-1,5-diene, cyclohexa-1,3-diene, isoprene, and 2,3-dimethylbuta-1,3-diene).

Subsequently other investigators have established that polymeric peroxides of low molecular weight are formed in the autoxidation of buta-1,3-diene[13,14], isoprene[15], 2-chlorobuta-1,3-diene[16,17], 2,3-dimethylbuta-1,3-diene[15,16-20], 2,4-dimethylpenta-1,3-diene[21], 2,5-dimethylhexa-2,4-diene[22,23], 2,6-dimethylocta-2,4,6-triene[24-28], cyclopentadiene[15,29], cyclohexa-1,3-diene[15,29,30], *p*-mentha-1,3-diene[31], 1,1′-bicyclohexenyl[32], and methyl octadeca-9,11-dienoate[33].

Study of the structure of copolymers of 1,3-dienes with oxygen has shown that oxygen can add on to dienes in both the 1,2 and the 1,4 positions:



Bodendorf[4] and Kern[15,18] found that thermal decomposition of the polyperoxide of 2,3-dimethylbuta-1,3-diene yields formaldehyde and 3-methylbut-3-en-2-one:

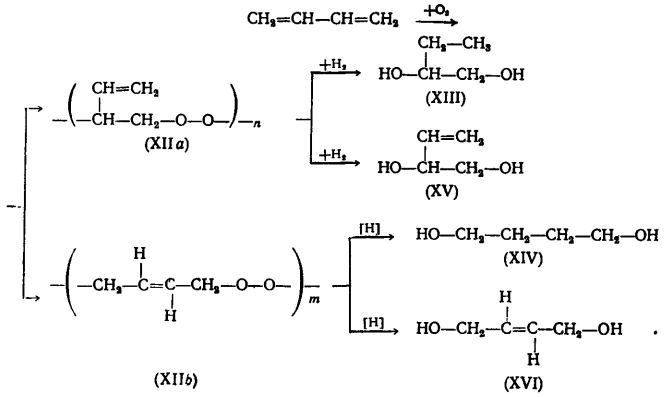


Later Kawahara[20] isolated formaldehyde, the above methylbutenone, αβ-dimethylenebutyraldehyde, and butane-2,3-dione from the decomposition products of this copolymer. Formation of the last two compounds from the copolymer is perhaps explained by the presence in it of 1,4 links as well as the 1,2 links.

Handy and Rothrock[14] established that both 1,2 and 1,4 addition of oxygen takes place in its copolymerisation with buta-1,3-diene, the latter predominating. Catalytic reduction of the polymeric peroxide — (XII*a*) and (XII*b*) — gave

† Other experimental results have been published[10-12] indicating the possible presence of (V) and (VI) in the product of the thermal isomerisation of ascaridole.

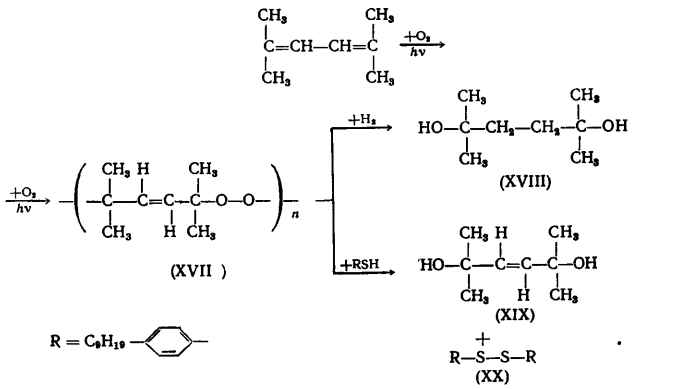
butane-1,2-diol (XIII) and a larger quantity of butane-1,4-diol (XIV), while its reduction with lithium tetrahydroaluminate yielded but-3-ene-1,2-diol (XV) and *trans*-but-2-ene-1,4-diol (XVI).



(XII*a*) (XIII) (XV) (XIV) (XII*b*) (XVI)

Analysis of the infrared spectrum of the copolymer (XII*a*) and (XII*b*) confirmed the chemical evidence of its structure.

Griesbaum et al.[23] have shown that the autoxidation of 2,5-dimethylhexa-2,4-diene is rigorously selective with the formation of a *trans*-1,4-polyperoxide (XVII). The structure and the configuration of this copolymer were proved by an analysis of the nuclear magnetic resonance and infrared spectra. The proton resonance spectrum revealed signals only from vinyl and methyl protons at relative intensities of 1 : 6. Hence it followed that the polyperoxide had the 1,4 structure. Analysis of the infrared spectrum showed that the double bond in the polyperoxide had the *trans* configuration. The *trans*-1,4 structure of the copolymer was confirmed also by a chemical method. Catalytic hydrogenation of the polyperoxide (XVII) produced 2,5-dimethylhexane-2,5-diol (XVIII), whereas reduction of the polyperoxide with *p*-nonylbenzenethiol gave *trans*-2,5-dimethylhex-3-ene-2,5-diol (XIX) and di-*p*-nonylphenyl disulphide (XX)‡:



(XVII) (XVIII) (XIX) (XX)

3. Synthesis of Ascaridole

Schenck and Ziegler[5,34-36] suggested that ascaridole is formed in plants by the diene condensation of *p*-mentha-1,3-diene with molecular oxygen under the photosensitising influence of chlorophyll. This hypothesis was verified by shaking a dilute alcoholic solution of *p*-mentha-1,3-diene in the presence of Eosin in an atmosphere of oxygen while exposed to a 300 W lamp. After completion of the photooxidation the solution was reduced in the presence of a palladium catalyst. *p*-Menthane-*cis*-1,4-diol (III) was isolated from the products. In a parallel experiment Schenck distilled off the solvent, and was able to obtain from the residue a preparation melting at 2.5°, a mixture of which with natural ascaridole showed no melting-point depression.

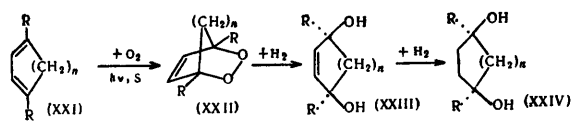
In further experiments Schenck carried out the photochemical diene synthesis of ascaridole in ethanol, propan-2-ol, acetone, and toluene in the presence of various photosensitisers (chlorophyll, Eosin, Erythrosin, Methylene Blue, Fluorescein, Pinacyanol, etc.). The photooxidation of *p*-mentha-1,3-diene in isopropyl alcohol in the presence of Methylene Blue gave a 25% yield of ascaridole. Pure synthetic ascaridole had m.p. 4.2°.

The catalytic hydrogenation of synthetic ascaridole over Raney nickel produced a 96% yield of *p*-menthane-*cis*-1,4-diol (III), whereas the reduction of ascaridole with a potassium–sodium alloy in ether gave a 57% yield of *p*-menth-2-ene-1,4-diol (II).

4. Epidioxides of Cyclopentadiene, Cyclohexa-1,3-diene, Cyclohepta-1,3-diene, and Their Derivatives

The photosensitised oxidation of cycloalka-1,3-dienes having five-, six-, and seven-membered rings and their derivatives has been studied by Schenck and other workers.

In 1952 Schenck[35,37,38] obtained a very unstable epidioxide of cyclopentadiene (XXII*a*) (5,6-dioxabicyclo[2,2,1]hept-2-ene) by the photosensitised oxidation of cyclopentadiene (XXI*a*) at -80°. On warming to 0° cyclopentadiene epidioxide decomposes explosively. Catalytic reduction of the epidioxide (XXII*a*) yielded cyclopentane-*cis*-1,3-diol (XXIV*a*), whereas reduction with thiourea at -20° gave cyclopent-4-ene-*cis*-1,3-diol (XXIII*a*).



(XXI) (XXII) (XXIII) (XXIV)

where S is the sensitiser; and for XXI–XXIV:

(*a*) $n = 1$; R = H,
(*b*) $n = 1$; R = C_6H_5,
(*c*) $n = 2$; R = H,
(*d*) $n = 3$; R = H,
(*e*) $n = 3$; R = C_6H_5.

Schenck[39,40] obtained the epidioxide (XXII*b*) by the photosensitised oxidation of 1,4-diphenylcyclopentadiene (XXI*b*), and reduced the product catalytically to the *cis*-1,3-diol (XXIII*b*). It was found that 1,4-diphenylcyclopentadiene (XXI*b*) can act as a photosensitiser both for its reaction with oxygen and for other diene syntheses of transannular epidioxides (e.g. the synthesis of ascaridole from *p*-mentha-1,3-diene). On heating, the epidioxide (XXII*b*) of 1,4-diphenylcyclopentadiene breaks down into oxygen and the original hydrocarbon (XXI*b*).

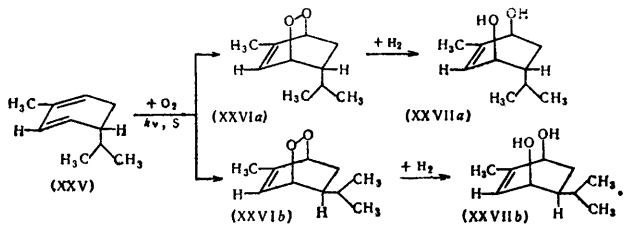
‡ See also Ref. 211 for the structure of the polymeric peroxide of 2,5-dimethylhexa-2,4-diene.

The photosensitised oxidation of cyclopentadienyltriphenyltin at -20° also gave an epidioxide, reduction of which at -20° with thiourea, with sodium tetrahydroborate, or catalytically resulted in an unsaturated *cis*-1,3-diol.[41]

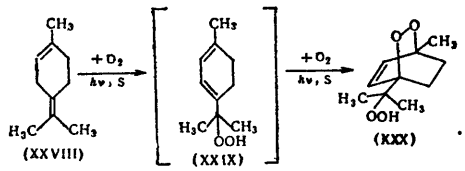
Schenck also found[5,35,37,38,42] that the photosensitised oxidation of cyclohexa-1,3-diene (XXI*c*) forms a crystalline epidioxide of cyclohexa-1,3-diene (XXII*c*) (5,6-dioxabicyclo[2,2,2]oct-2-ene)§.

In 1957 Cope[43] showed that the photosensitised oxidation of cyclohepta-1,3-diene (XXI*d*) involves formation of the crystalline epidioxide (XXII*d*), catalytic reduction of which produced the *cis*-1,4-diol (XXIV*d*). Later Courtot[44,45] established that a crystalline transannular epidioxide (XXII*e*) is formed by the photosensitised oxidation of 1,4-diphenylcyclohepta-1,3-diene (XXI*e*). The product was reduced catalytically to the *cis*-1,4-diol (XXIV*e*).

By the photosensitised oxidation of *p*-mentha-1,5-diene (XXV) Schenck[5,35,38,42] obtained two crystalline stereoisomeric epidioxides (XXVI*a*) and (XXVI*b*), which were reduced to the stereoisomeric unsaturated *cis*-1,4-diols (XXVII*a*) and (XXVII*b*):



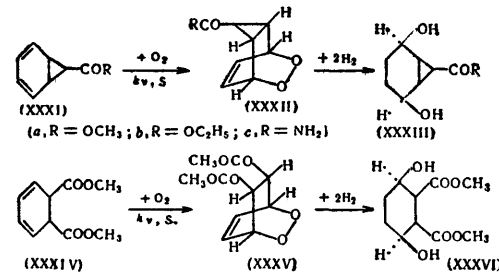
Schenck[38] also showed that the photosensitised oxidation of *p*-mentha-1,4(8)-diene (XXVIII) initially involves migration of the double bond with formation of *p*-mentha-1,3-diene 8-hydroperoxide (XXIX), when then condenses with a second molecule of oxygen by a mechanism of diene synthesis to form the extremely unstable ascaridole 8-hydroperoxide (XXX):



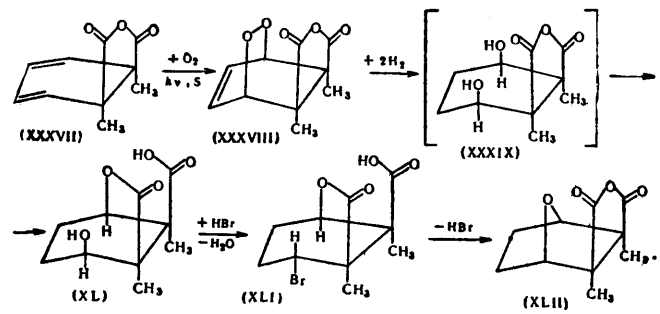
Schenck[35,38,46] studied the photosensitised oxidation of methyl and ethyl norcaradienecarboxylates (XXXI*a*) and (XXXI*b*) and dimethyl 1,2-dihydrophthalate (XXXIV). Oxidation of the first two esters gave the epidioxides (XXXII*a*) and (XXXII*b*), which on catalytic reduction were converted into the saturated 1,4-diols (XXXIII*a*) and (XXXIII*b*). These epidioxides were transformed into the amide (XXXII*c*) by the action of ammonia, the same amide being obtained by the photooxidation of norcaradienecarboxyamide (XXXI*c*).

§ In 1951 Hock established[29,30] that a very small yield of the epidioxide of cyclohexa-1,3-diene (XXII*c*) is formed by the autoxidation of cyclohexa-1,3-diene.

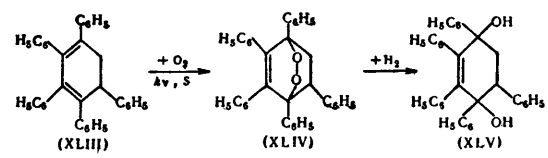
Photooxidation of the ester (XXXIV) enables Schenck to obtain the epidioxide (XXXV), catalytic reduction of which resulted in the saturated 1,4-diol (XXXVI):



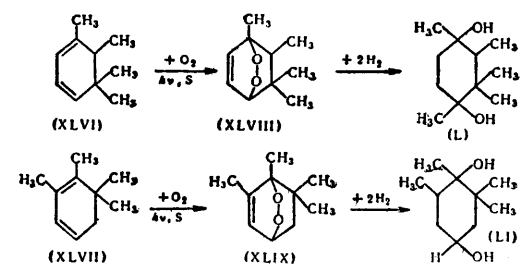
In 1953 Schenck[38,47] accomplished the stereospecific synthesis of cantharidin. The photochemical diene condensation of synthetic dehydrocantharidin (XXXVII) with oxygen gave dehydrocantharidin epidioxide (XXXVIII), in which the peroxide bridge occupies the same spatial position as the ether bridge in natural cantharidin. Catalytic hydrogenation of the epidioxide (XXXVIII) formed the diol (XXXIX), which under the experimental conditions underwent lactonisation to hydrohydroxycantharic acid (XL). The action of hydrogen bromide on the product yielded hydrobromocantharic acid (XLI), thermal decomposition of which gave cantharidin (XLII):



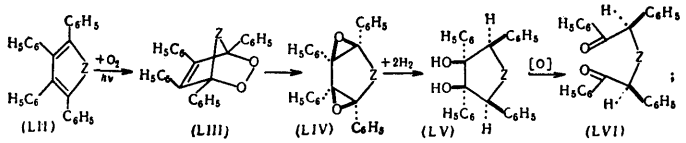
Bergmann[48] studied the photosensitised oxidation of 1,2,3,4,5-pentaphenylcyclohexadiene (XLIII), obtaining the epidioxide (XLIV), catalytic reduction of which gave the unsaturated 1,4-diol (XLV):



Schenck[35,42] investigated the photosensitised oxidation of 1,5,5,6- and 1,2,6,6-tetramethylcyclohexa-1,3-diene (XLVI) and (XLVII). He obtained the corresponding transannular epidioxides (XLVIII) and (XLIX), catalytic hydrogenation of which gave the saturated 1,4-diols (L) and (LI):

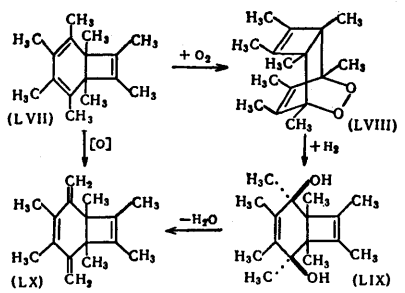


Dufraisse[49] showed that the photochemical oxidation of 2,3,4,5-tetraphenylcyclopentadiene (LII*a*) forms the epidioxide (LIII*a*), which on heating isomerises into the diepoxide (LIV*a*). The structure of the latter was proved by its reduction to the *cis*-1,2-diol (LV*a*), oxidation of which with iodic acid or lead tetraacetate gave 1,2,4,5-tetraphenylpentane-1,5-dione (LVI*a*).

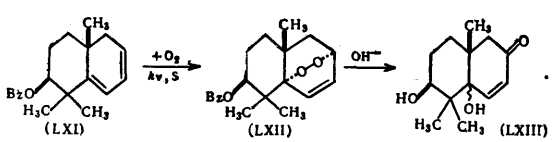


(*a*) Z = >CH_2; (*b*) Z = >C = CH_2.

Dufraisse[50] also found that the photooxidation of 2,3,4,5-tetraphenylfulvene (LII*b*) gave the epidioxide (LIII*b*), which under the experimental conditions isomerised into the diepoxide (LIV*b*). The latter was reduced with lithium tetrahydroaluminate to the *cis*-1,2-diol (LV*b*), which was oxidised with lead tetraacetate to 3-methylene-1,2,4,5-tetraphenylpentane-1,5-dione (LVI*b*).



In 1962 Criegee[51,52] reported that the 1,2,3,4,5,6,7,8-octamethylbicyclo[4,2,0]octa-2,4,7-triene (LVII) which he had synthesised was oxidised so readily that it could be prepared only when oxygen was completely excluded. In air this hydrocarbon oxidises quantitatively to a crystalline peroxide after a few hours. Examination of the infrared, ultraviolet, and nuclear magnetic resonance spectra of the product showed it to be a transannular epidioxide (LVIII). When a methanolic solution of the hydrocarbon (LVII) was shaken with oxygen for 20 min, exactly one molecule of oxygen was absorbed, the peroxide being formed at the same rate in the light and in the dark. This represents the first case of the formation of an epidioxide in a dark reaction. Nor did addition of inhibitors affect the rate of oxidation of the hydrocarbon (LVII)¶. The epidioxide (LVIII) was reduced to the diol (LIX), dehydration of which yielded the hydrocarbon (LX). The same hydrocarbon was obtained by the oxidation of (LVII) with silver nitrate, chloranil, or benzoquinone. Criegee found that the octamethylbicyclooctatriene (LVII) forms diene adducts with tetracyanoethylene and azoformic ester, but does not react with maleic anhydride or acetylenedicarboxylic ester even at 140°.



Halsall[53,54] established that exposure of a dilute alcoholic solution of 1,2,3,4,5,10-hexahydro-1,1,10β-trimethyl-2β-naphthyl benzoate (LXI) to the light from a 500 W lamp in the presence of Eosin and oxygen results in the formation of the 6α,9α-epidioxide (LXII), which in alkaline medium is converted into an αβ-unsaturated ketone (LXIII). The oxygen bridge in the epidioxide (LXII) must be assumed to have the α configuration, since the 1- and 10-methyl groups prevent attack on the diene (LXI) from the β side.

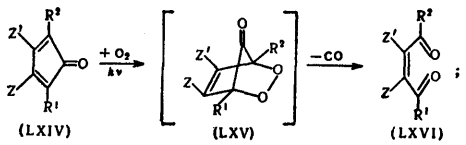
5. Photooxidation of Arylated Cyclopentadienones (Cyclones) and Arylated Cyclopentadienols

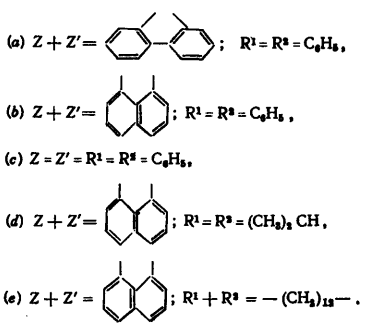
In 1938 Dilthey[55] discovered that, when solutions of phencyclone (LXIV*a*) in pyridine or toluene are exposed to sunlight in the presence of air, 9,10-dibenzoylphenanthrene (LXVI*a*) is formed. In the photochemical oxidation of acecyclone (LXIV*b*) in chlorobenzene medium in air, 1,2-dibenzoylacenaphthylene (LXVI*b*) is obtained[55].

Schenck[56], Dufraisse[57,58], Becker[59], and Wilcox[60] have established the formation of 1,2,3,4,-tetraphenylbut-*cis*-2-ene-1,4-dione (LXVI*c*) and carbon monoxide in the photooxidation of tetracyclone (LXIV*c*).

In 1953 Allen[61] reported that photooxidation of the cyclones (LXIV*d*) and (LXIV*e*) yields the 1,4-diketones (LXVI*d*) and (LXVI*e*).

It must be assumed that the photooxidation of cyclones (LXIV*a–e*) involves the initial formation of unstable diene adducts having an *endo*-carbonyl bridge (LXV*a–e*), which under the experimental conditions break down into carbon monoxide and 1,4-dicarbonyl compounds (LXVI*a–e*)†.



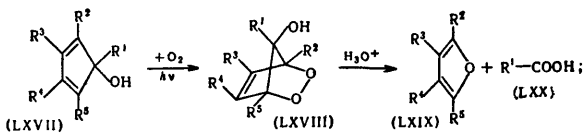


Dufraisse[57,58] and Rio[63] established that in the photooxidation of pentaarylcyclopentadienols (LXVII*a–f*) the corresponding photoperoxides (LXVIII*a–f*) are formed, and these on being heated with acetic acid undergo fission

¶ 1,2,3,4,5,6-Hexamethylcyclohexa-1,3-diene, which was synthesised for comparison, did not oxidise in the dark.

† The mechanism of the photooxidation of cyclones has been discussed by Syrkin and Moiseev[62].

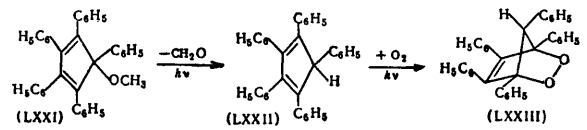
with the formation of tetraarylfurahs (LXIX*a–f*) and aromatic acids (LXX*a–f*):



(LXVII) (LXVIII) (LXIX) + R'—COOH; (LXX)

(*a*) $R^1 = R^2 = R^3 = R^4 = R^5 = C_6H_5$,
(*b*) $R^2 = R^3 = R^4 = R^5 = C_6H_5$; $R^1 = p\text{-}(CH_3)_2NC_6H_4$,
(*c*) $R^1 = R^2 = R^4 = R^5 = C_6H_5$; $R^3 = p\text{-}(CH_3)_2NC_6H_4$,
(*d*) $R^2 = R^3 = R^4 = R^5 = C_6H_5$; $R^1 = p\text{-}CH_3C_6H_4$,
(*e*) $R^1 = R^3 = R^4 = R^5 = C_6H_5$; $R^2 = p\text{-}CH_3C_6H_4$,
(*f*) $R^1 = R^2 = R^4 = R^5 = C_6H_5$; $R^3 = p\text{-}CH_3C_6H_4$.

The photooxidation of 1-methoxypentaphenylcyclopentadiene (LXXI) at first involves photolysis with production of formaldehyde and pentaphenylcyclopentadiene (LXXII), which undergoes photooxidation to form an epidioxide (LXXIII):[57]



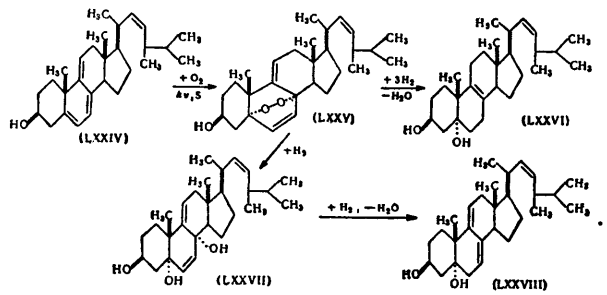
(LXXI) (LXXII) (LXXIII)

6. Steroid Epidioxides

In 1928 Windaus[64], while studying the conversion of ergosterol [24-methylcholesta-5,7,22-trien-3β-ol] into vitamin D_2 [ergocalciferol], found that irradiation of dilute alcoholic solutions of the former with a 200 W lamp in the presence of a photosensitiser (Eosin, Erythrosin) and air led to the addition of a molecule of oxygen to a molecule of ergosterol, the product possessing the properties of a peroxide and being termed ergosterol peroxide. The photosensitised oxidation of 24-methylcholesta-5,7,9(11),22--tetraen-3β-ol under the same conditions[65–67], produced "9(11)-dehydroergosterol peroxide".

It was subsequently found that other homoannular steroid 1,3-dienes are readily converted into peroxides. Peroxides were prepared from 24-methylcholesta-5,7-dien-3β-ol[68], 3β-acetoxy-24-methylcholesta-6,8(14),9(11),22-tetraene,[69–72] 3-acetoxy-2-methylcholesta-3,5,7,22-tetraene[73], 3-acetoxy-24-methylcholesta-3,5,7,9(11),22-pentaene[73], 3-acetoxy-5α-pregna-6,8(14),9(11)-trien-20-one[71,72], 3β,21-diacetoxy-5α-pregna-6,8(14),9(11)-trien-20-one[71], lumisteryl acetate [3-acetoxy-24-methyl-10α-cholesta--5,7,22-triene][74], [3-acetoxy-24-methyl-10α-cholesta--5,7,9(11),22-tetraene[74], cholesta-5,7-dien-3β-ol[75,77], 3β-acetoxycholesta-5,7-diene[76], cholesta-5,7,24-trien--3β-ol[77], cholesta-2,4-diene[78–80], cholesta-1,3,5-trien--7-one[81], and androsta-5,7-diene-3,17-diol[82].

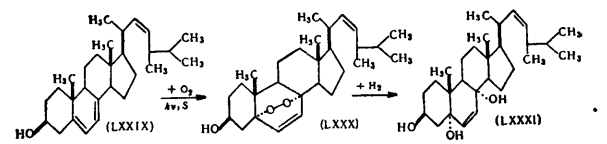
Examination of the ultraviolet spectrum of the peroxide obtained from 24-methylcholesta-5,7,9(11),22-tetraen-3β--ol (LXXIV) showed that it did not contain a conjugated system of double bonds, and on catalytic reduction formed a 24-methylcholestadienediol, for which the structure (LXXVI) was established[67]. From these results it was concluded that the dehydroergosterol peroxide had the structure (LXXV)[67]. The formation of the diol (LXXVI) on catalytic hydrogenation of the transannular epidioxide (LXXV) is explained by initial formation of the 3,5,8-triol, which is dehydrated with formation of a double bond between $C_{(8)}$ and $C_{(9)}$.



(LXXIV) (LXXV) (LXXVI) (LXXVII) (LXXVIII)

When the epidioxide (LXXV) was reduced with zinc and alcoholic alkali, a trienediol was obtained[67,83], whose ultraviolet spectrum showed it to contain two conjugated cyclic double bonds. The trienediol gave no diene adduct with maleic anhydride, so that its conjugated double bonds were present in different rings. On the basis of these results the structure (LXXVIII) was assigned to the trienediol. Its formation probably involved reduction of the epidioxide (LXXV) to the trienetriol (LXXVII) followed by elimination of the 8-hydroxyl and migration of a cyclic double bond to a conjugated position.

In 1950 Fieser[84,85] adduced weighty arguments in support of the α configuration for the oxygen bridge in steroid epidioxides. During 1952–1954 Bladon et al.[86–89] established the α configuration for the oxygen bridge in 24-methylcholesta-5,7,9(11),22-tetraen-3-ol epidioxide (LXXV), and described a method for preparing cortisone from it.

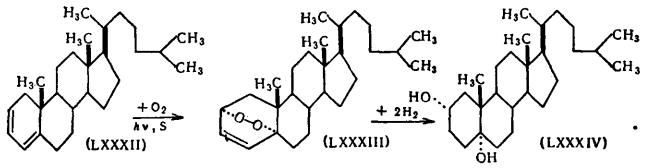


(LXXIX) (LXXX) (LXXXI)

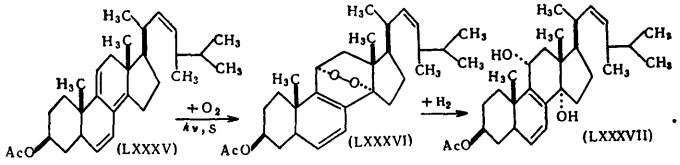
By the photosensitised oxidation of ergosterol (LXXIX) Windaus[64–66] obtained its peroxide, which was reduced with zinc and alcoholic alkali to a dienetriol. Study of the chemical reactions of the latter led Achtermann[90], Müller[67], and Heilbron[91] to conclude that the epidioxide bridge had been attached to $C_{(5)}$ and $C_{(6)}$. However, in 1936 Fieser[92] cited convincing evidence (see also Ref. 85, p. 96) indicating that the reduction product was a 3,5,8-triol (LXXXI), which could be formed only from a transannular epidioxide (LXXX). In 1939 Bergmann[93] agreed with Fieser's view, that the epidioxide of ergosterol had the structure (LXXX). Fieser[84] in 1950 and Henbest and Jones[94] in 1953 showed that the oxygen bridge in the epidioxide had the α configuration.

In 1947 Wieland and Prelog[95] isolated the epidioxide (LXXX) from the mycelia of the mould *Aspergillus fumigatus*, and in 1964 Bauslaugh et al.[96] isolated it from the mycelia of *Trichophyton schönleini*. The epidioxide (LXXX) was identified by the method of mixed melting points with a synthetic specimen[95,96]. The identity of the two samples was confirmed by examination of the infrared, nuclear magnetic resonance, and mass spectra[96].

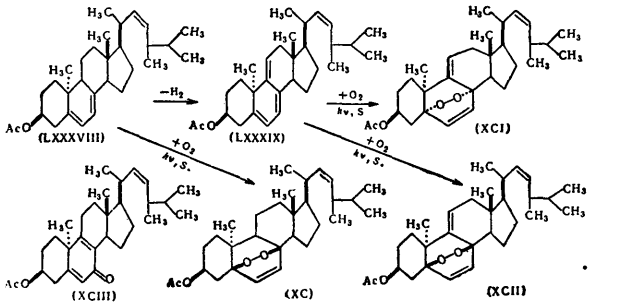
By catalytic reduction of the epidioxide of cholesta-2,4--diene Bergmann[79,80,93] obtained a saturated diol, for which he established the structure (LXXXIV). Hence the product of the photosensitised oxidation of cholesta-2,4--diene (LXXXII) was the epidioxide (LXXXIII). In 1953 he showed[97] that the oxygen bridge in the epidioxide (LXXXIII) had an α configuration.



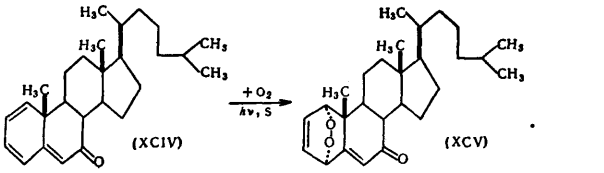
During 1953–1956 Laubach[69,70] established that the photosensitised oxidation of 3β-acetoxy-24-methylcholesta--6,8(14),9(11),22-tetraene (LXXXV) gives the 11α,14α-epidioxide (LXXXVI), hydrogenation of which in the presence of Lindlar's catalyst yielded 3β-acetoxy-24-methylcholesta-6,8,22-triene-11α,14α-diol (LXXXVII). He developed[98,70] a method for preparing from the epidioxide (LXXXVI) the compound 3-acetoxy-24-methylcholesta--8,22-dien-11-one, from which cortisone can be obtained.



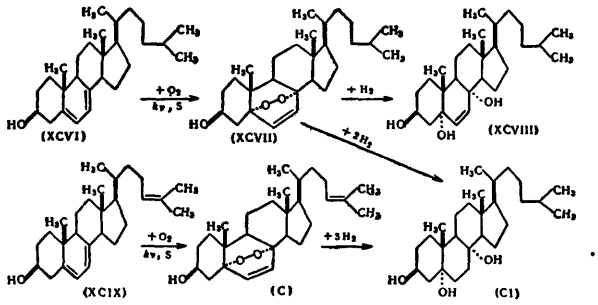
In 1955 Bladon[74] found that the photosensitised oxidation of 3β-acetoxy-24-methyl-10α-cholesta-5,7-22-triene (LXXXVIII) yields 3β-acetoxy-24-methyl-10α-cholesta--5,7,9(11),22-tetraene (LXXXIX), the β-epidioxide (XC) of (LXXXVIII), the α-epidioxide (XCI) of (LXXXIX), the β-epidioxide (XCII) of (LXXXIX), and 3β-acetoxy-24--methyl-10α-cholesta-5,8,22-trien-7-one (XCIII). Photooxidation of (LXXXIX) gave the α-epidioxide (XCI) and the β-epidioxide (XCII).



In 1956 Henbest[81] reported that the photosensitised oxidation of cholesta-1,3,5-trien-7-one (XCIV) produces the α-epidioxide (XCV):



In 1936 Schenck[75] found that the photosensitised oxidation of cholesta-5,7-dien-3β-ol (XCVI) involves formation of its epidioxide. Reduction of the latter with zinc and alcoholic alkali gave a cholestenetriol. From the results of a study of the structure and chemical reactions of epidioxides of other steroids, the compound formed from (XCVI) was to be regarded as the 5α,8α-epidioxide (XCVII), and its reduction product as having the structure cholest-6--ene-3β,5α,8α-triol (XCVIII). During 1963–1964 Dvornik and Kraml[77,99] prepared epidioxides from cholesta-5,7--dien-3β-ol (XCVI) and from cholesta-5,7,24-trien-3β-ol (XCIX), and reduced them catalytically.



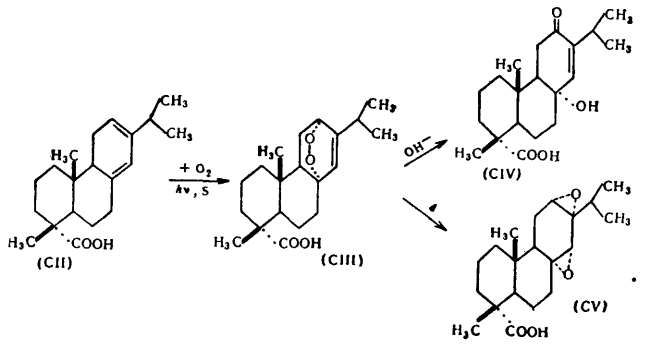
Dvornik and Kraml studied the mechanism of the conversion of lanosterol [4,4,14-trimethylcholesta-8,24-dien-3β-ol] into cholesterol [cholest-5-en-3β-ol] during the biochemical synthesis of the latter in cholesterologenic tissues. The method used in this investigation was to inhibit enzymes responsible for individual stages in the biosynthesis of cholesterol. These workers were able to detect in rat blood serum a steroid, examination of whose ultraviolet spectrum showed it to be a homoannular conjugated diene. They isolated from rat's liver a steroid which they identified as a transannular epidioxide (XCVII) of cholesta-5,7--dien-3β-ol (XCVI). Pig's liver was found to contain a steroid having an ultraviolet spectrum typical of homoannular conjugated diene steroids. The compound was identified by conversion into a transannular epidioxide, which was isolated in an analytically pure form and identified as 5α,8α-epidioxycholesta-6,24-dien-3β-ol (C). The structure of the latter was established by catalytic reduction with platinum oxide to cholestane-3β,5α,8α-triol (CI), which proved to be identical with a known specimen of this triol, prepared by the photosensitised transannular addition of oxygen to cholesta-5,7-dien-3β-ol (XCVI) followed by catalytic reduction of the resulting epidioxide (XCVII) to the triol (CI). Examination of the nuclear magnetic resonance spectrum of the epidioxide (C) supported the chemical evidence of its structure.

Dvornik and Kraml's investigation has shown that cholesta-5,7-dien-3β-ol (XCVI) is an intermediate in the biosynthesis of cholesterol, and that cholesta-5,7,24--trien-3β-ol (XCIX) is probably a precursor of (XCVI) in this process.

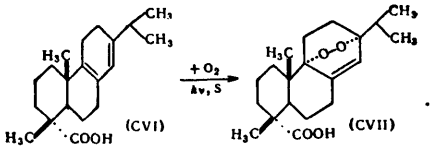
In 1964 Blondin et al.[100] reported that [4-^{14}C]cholesta--5,7-dien-3β-ol is converted into radioactive cholecalciferol in a homogenate of bass liver incubated in the dark. They suggested that 5α,8α-epidioxycholest-6-en-3β-ol (XCVII) may be an intermediate in this non-photochemical reaction. An experiment undertaken to verify this hypothesis showed that cholesta-5,7-dien-3β-ol (XCVI) is converted into the 5α,8α-epidioxide (XCVII) in a homogenate of fish liver incubated in the dark.

7. Epidioxides of Resin Acids

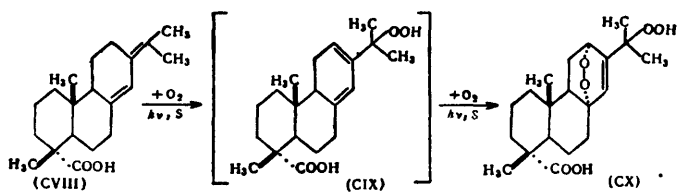
In 1958 Moore and Lawrence[101-104] discovered that the photosensitised oxidation of laevopimaric acid (CII) involves the formation of a crystalline transannular epidioxide — 6α,14α-epidioxy-Δ⁷-dodecahydro-7-isopropyl--1β,12β-dimethylphenanthrene-1α-carboxylic acid (CIII)‡ — which in alkaline medium is converted into Δ⁷-dodecahydro-14α-hydroxy-7-isopropyl-1β,12β-dimethyl-6-oxophenanthrene-1α-carboxylic acid (CIV). When a xylene solution of the epidioxide is boiled, the latter rearranges into 6,7α : 8,14α-diepoxytetradecahydro-7-isopropyl-1β,12β--dimethylphenanthrene -1α-carboxylic acid (CV):[104]



In 1960 Schuller, Moore, and Lawrence[103,104,107] reported that the photosensitised oxidation of palustric acid (CVI) gives a crystalline epidioxide — 7α,13α-epidioxy-Δ⁸-dodecahydro-7-isopropyl-1β,12β-dimethylphenanthrene-1α-carboxylic acid (CVII):



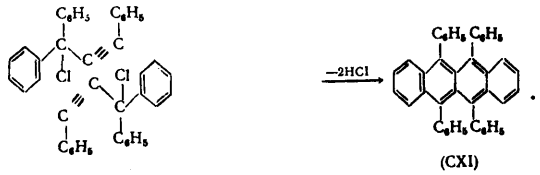
Schuller and Lawrence[104-106] also established that the photosensitised oxidation of neoabietic acid (CVIII) first involves a monoene addition and migration of a double bond to form the 18-hydroperoxy-derivative (CIX) of laevopimaric acid, which reacts further with a second molecule of oxygen by a diene addition mechanism to form a diperoxide — 6α,14α-epidioxy-Δ⁷-dodecahydro-7-(2--hydroperoxyprop-2-yl)-1β,12β-dimethylphenanthrene-1α--carboxylic acid (CX):



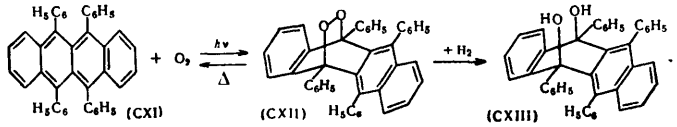
‡ Lawrence[106] attributes an α configuration to the oxygen bridge in the epidioxides of resin acids, since the β-methyl groups prevent attack from the β region on the 1,3-diene system of the resin acids, as in the case of steroids.

III. REACTION OF MOLECULAR OXYGEN WITH AROMATIC DIENES

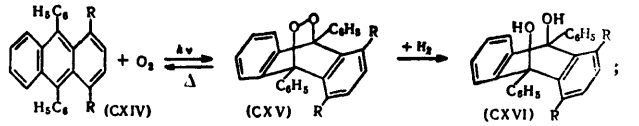
In 1926 Moureu and Dufraisse[108] observed that, when 3-chloro-1,3,3-triphenylprop-1-yne is heated in a vacuum to 100–120°, hydrogen chloride is evolved, and a red hydrocarbon having the composition $C_{42}H_{28}$ is formed. The name of this hydrocarbon is rubrene. These workers established[108] that dilute solutions of rubrene in benzene, carbon disulphide, chloroform, and other solvents rapidly lose their colour on exposure to sunlight or artificial light in the presence of air. A compound possessing the properties of a peroxide and having the composition $C_{42}H_{28}O_2$ was isolated from the decolorised solutions. When rubrene peroxide was heated in a vacuum to 140–150°, it broke down into the original hydrocarbon and oxygen. This decomposition was accompanied by luminescence. It was established[109,110] in 1936 that rubrene was 5,6,11,12-tetraphenylnaphthacene (CXI)§.



In 1937 Dufraisse[112] observed that catalytic reduction of rubrene peroxide gave the 5,12-diol (CXIII), which had been obtained previously by the action of phenyllithium on 6,11-diphenylnaphthacene-5,12-quinone[110] and by the action of potassium permanganate on rubrene[113]. Since rubrene peroxide gave the 5,12-diol (CXIII) on reduction, it must have been a transannular epidioxide (CXII):



By irradiating solutions of 9,10-diphenylanthracene (CXIV*a*) in the presence of air, Dufraisse[114,115] obtained a peroxide of this compound, reduction of which gave the 9,10-diol (CXVI*a*). Consequently the peroxide of 9,10-diphenylanthracene had the transannular structure (CXV*a*). When heated in a vacuum to 180°, the epidioxide of 9,10-diphenylanthracene (CXV*a*) decomposes into oxygen and the original hydrocarbon (CXIV*a*).

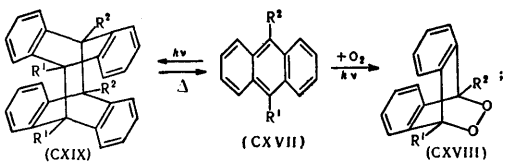


(*a*) R = H; (*b*) R = OCH_3.

By the photooxidation of 1,4-dimethoxy-9,10-diphenylanthracene (CXIV*b*) Dufraisse[116,117] obtained the transannular epidioxide (CXV*b*), which slowly dissociated into the original components even at room temperature.

§ For the mechanism of the formation of rubrene from 3-chloro--1,3,3-triphenylprop-1-yne, see Ref.111.

It was also found[118-121] that irradiation in the presence of air of dilute carbon-disulphide solutions of anthracene (CXVII*a*), 9-methylanthracene (CXVII*b*), 9-ethylanthracene (CXVII*c*), 9,10-dimethylanthracene (CXVII*d*), and 9-ethyl-10-methylanthracene (CXVII*e*) yields the transannular epidioxides (CXVIII*a–e*), which when heated in a vacuum decompose violently without the evolution of free oxygen:



(CXIX) (CXVII) (CXVIII)

(*a*) $R^1 = R^2 = H$,
(*b*) $R^1 = H$; $R^2 = CH_3$,
(*c*) $R^1 = H$; $R^2 = C_2H_5$,
(*d*) $R^1 = R^2 = CH_3$,
(*e*) $R^1 = CH_3$; $R^2 = C_2H_5$.

When solutions of anthracene (CXVII*a*), 9-methylanthracene (CXVII*b*), and 9,10-dimethylanthracene (CXVII*d*) in benzene, xylene, glacial acetic acid, and other solvents are exposed at room temperature in the absence of air, photodimers (CXIX*a*), (CXIX*b*), and (CXIX*d*) are formed. This reaction is reversible: the anthracenes are regenerated when the temperature is raised in the dark. Other anthracene derivatives also form photodimers. However, neither 9,10-diphenylanthracene (CXIV*a*) nor rubrene (CXI) undergoes photochemical dimerisation. This may be due to steric hindrance, or else to thermal instability of the photodimers under the experimental conditions[122].

Dufraisse, Clar, Étienne, and other investigators have established that transannular epidioxides are formed by various linear and angular fusion products of anthracene with benzene rings, several of their derivatives, and nitrogen analogues[123-126]. All attempts to prepare photoperoxides of naphthalene, phenanthrene, or acridine were unsuccessful[127,128].

Hence it follows that transannular photoepidioxides are formed only from polycyclic aromatic compounds which contain an anthracene ring system (acenes). These compounds contain a reactive aromatic diene system (an *o*-quinoid grouping), and are capable of undergoing diene synthesis with maleic anhydride, *p*-benzoquinone, azoformic ester, and other dienophiles. The photooxidation of acenes can therefore be regarded as a photochemical diene synthesis with molecular oxygen.

Anthracene, 9,10-diphenylanthracene, rubrene, and other acenes act as sensitisers, and therefore do not require the addition of other photosensitisers for their photooxidation. Acenes can be used also as photosensitisers in the oxidation of other organic compounds. In the presence of rubrene, for examples, *p*-mentha-1,3--diene is oxidised to ascaridole[39,40].

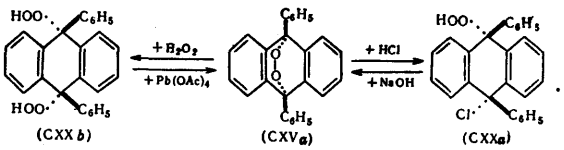
The rate of formation of acene epidioxides is greatly dependent on the nature of the solvent. Thus Dufraisse[129] found the relative rates of photooxidation of rubrene in various solvents to be as indicated in the accompanying Table.

Study of the chemical reactions of the photoperoxides of acenes has given interesting results. For example, Pinazzi[130] established that 9,10-diphenylanthracene photoepidioxide (CXV*a*) reacts with hydrogen chloride to form

TABLE.

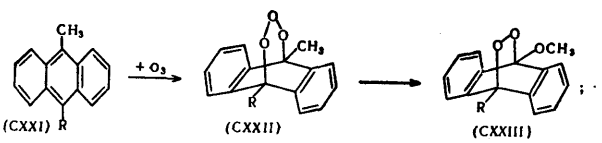
Solvent	Relative rate of photooxidation of rubrene (benzene = 1)
Carbon disulphide	9
Chloroform	3
Ethyl iodide	1
Benzene	1
Acetone	1
Ether	0.5
Anisole	0.4
Pyridine	0.25
Nitrobenzene	0.10

a chloro-hydroperoxide (CXX*a*), which yields the original peroxide (CXV*a*) on treatment with alkali. He also observed[131] that the epidioxide (CXV*a*) reacts with hydrogen peroxide to form a dihydroperoxide (CXX*b*). Criegee[132] obtained the original 9,10-diphenylanthracene epidioxide (CXV*a*) from the latter by treatment with lead tetraacetate.



(CXX*b*) (CXV*a*) (CXX*a*)

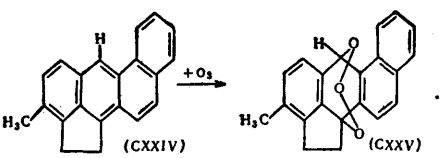
It has recently been found[133,134] that 9,10-dimethylanthracene (CXXI*a*) and 9-methoxy-10-methylanthracene (CXXI*b*) in dichloromethane react at -78° with ozone to form monoozonides. The nuclear magnetic resonance spectra of the latter show them to be transannular-9,10-adducts (CXXII*a*) and (CXXII*b*). In solution these adducts are rapidly converted even at room temperature into the transannular 9,10-epidioxides (CXXIII*a*) and (CXXIII*b*).



(CXXI) (CXXII) (CXXIII)

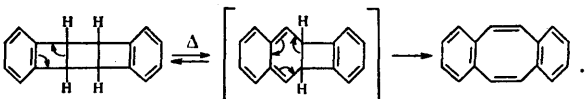
(*a*) R = CH_3; (*b*) R = OCH_3.

The ozonisation of 3-methylcholanthrene (CXXIV) in dichloromethane at -78° gave a mixture of peroxides, which probably contained the transannular 6,12b-ozonide (CXXV).[135]



(CXXIV) (CXXV)

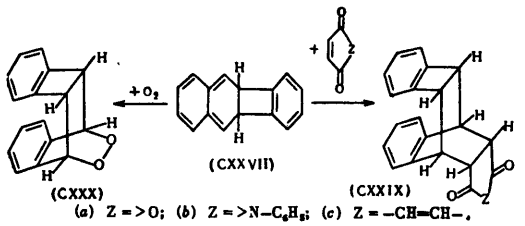
Nenitzescu has shown[136-138] that the linear dimer (CXXVI) of benzocyclobutadiene rearranges on heating to form 1,2 : 5,6-dibenzocyclooctatetraene (CXXVIII). He[137,138] as well as Cava[139] put forward the hypothesis that this change involves two consecutive reactions — (1) reversible isomerisation of (CXXVI) into an unstable hydrocarbon of *o*-quinoid structure (CXXVII), and (2) rearrangement of the latter to (CXXVIII):



(CXXVI) (CXXVII) (CXXVIII)

This mechanism for the rearrangement was confirmed by trapping the intermediate *o*-quinoid compound (CXXVII) with

various dienophiles: heating the hydrocarbon (CXXVI) with maleic anhydride, *N*-phenylmaleimide, and *p*-benzoquinone gave the corresponding diene adducts (CXXIX*a–c*)[137–139].



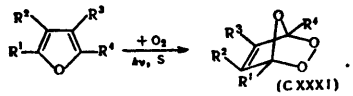
(CXXX) (CXXVII) (CXXIX)

(*a*) Z = >O; (*b*) Z = >N–C_6H_5; (*c*) Z = –CH=CH–.

Nenitzescu[137,138] also found that, when a stream of oxygen is passed through an ethereal solution of dibenzotricyclooctadiene (CXXVI), a crystalline peroxide is formed, to which he attributed the transannular structure (CXXX). This peroxide is sparingly soluble in the usual solvents, and Nenitzescu does not exclude the possibility that it may be a polymeric compound. Catalytic reduction of the peroxide yields, instead of the expected diol, a hydrocarbon having the composition $C_{16}H_{16}$.

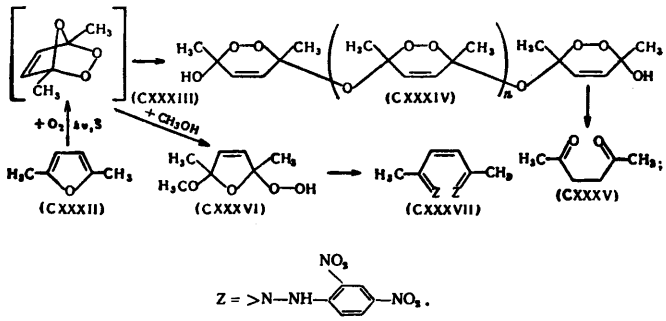
IV. REACTION OF MOLECULAR OXYGEN WITH 1,3-DIENES CONTAINING HETEROATOMS

In 1952 Schenck[35,38,140–142] reported that furan and its derivatives on exposure to light in the presence of a photosensitiser, react with molecular oxygen by a mechanism of diene synthesis to form extremely unstable adducts of ozonide structure (CXXXI), which cannot be isolated¶:



(CXXXI)

The first attempt at photosensitised oxidation was undertaken with 2,5-dimethylfuran (CXXXII). A dilute alcoholic solution of this compound containing Eosin was shaken in an atmosphere of oxygen while exposed to a 300 W lamp for 10 days. The photooxidation product possessed peroxide properties, and from it was isolated a crystalline polymeric peroxide, catalytic hydrogenation of which gave a quantitative yield of hexane-2,5-dione (CXXXV). Hence, in the photosensitised oxidation of 2,5-dimethylfuran, the oxygen had added on at the 2,5 positions to form a readily polymerisable diene adduct of ozonide structure (CXXXIII). Schenck assumes that the polymeric peroxide which he isolated had the structure (CXXXIV).

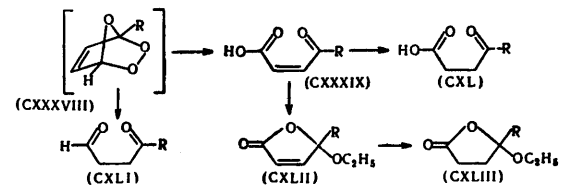


(CXXXIII) (CXXXIV) (CXXXII) (CXXXVI) (CXXXVII) (CXXXV)

Z = >N–NH–$C_6H_3(NO_2)_2$.

In 1964 Foote[147] established that the photosensitised oxidation of 2,5-dimethylfuran (CXXXII) in methanol gives a 74% yield of a crystalline peroxide having the composition $C_7H_{12}O_4$. Examination of the infrared and nuclear magnetic resonance spectra of this peroxide showed it to be 2,5-dihydro-2-hydroperoxy-5-methoxy-2,5-dimethylfuran (CXXXVI). This was converted into the known bis-2,4-dinitrophenylhydrazone of hex-*cis*-3-ene-2,5-dione (CXXXVII). Foote assumes that the photooxidation of (CXXXII) involves the initial formation of a diene adduct of ozonide structure (CXXXIII), which then reacts with the methanol to form the hydroperoxide (CXXXVI).

By the photosensitised oxidation of 2-methylfuran Schenck[140] obtained a peroxide of ozonide structure (CXXXVIII*a*), catalytic hydrogenation of which gave γ-oxovaleraldehyde (CXLI*a*) and γ-oxovaleric acid (CXL*a*). The latter was formed by rearrangement of the peroxide (CXXXVIII*a*) to 4-oxopent-*cis*-2-enoic acid (CXXXIX*a*) followed by hydrogenation. The rearrangement of the adduct (CXXXVIII*a*) to (CXXXIX*a*) readily occurs in alcoholic solution in the presence of vanadium pentoxide. Under these conditions 2-methylfuran gave a 76% yield of the ethyl ether (CXLII*a*) of the lactol form of the acid (CXXXIX*a*), catalytic reduction of which formed the ethyl ether (CXLIII*a*)†.



(CXXXVIII) (CXXXIX) (CXL) (CXLI) (CXLII) (CXLIII)

(*a*) R = CH_3; (*b*) R = H; (*c*) R = COOH.

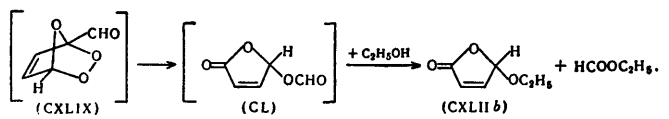
Schenck[140] obtained by the photosensitised oxidation of furan an adduct of ozonide structure (CXXXVIII*b*), which rearranged rapidly to 4-oxobut-*cis*-2-enoic acid (CXXXIX*b*), catalytic reduction of which formed γ-oxobutyric acid (CXL*b*). When rearrangement of the adduct (CXXXVIII*b*) was carried out in ethanol medium, the ethyl ether (CXLII*b*) of the lactol form of (CXXXIX*b*) was obtained, and was reduced to the ethyl ether (CXLIII*b*) of the lactol form of (CXL*b*).

By the photosensitised oxidation of 2-furoic acid and furfural in ethanolic medium Schenck[140] obtained high yields of the ethyl ether (CXLII*b*) of the lactol form of 4-oxobut-*cis*-2-enoic acid. In the former case the intermediate diene adduct (CXXXVIII*c*) is immediately decarboxylated with formation of the adduct (CXXXVIII*b*), which is then converted into the pseudo-ester (CXLII*b*). In the second case the reaction probable involves the initial formation of a diene adduct (CXLIX), which then rearranges to the mixed anhydride (CL) of the lactol form of 4-oxobut-*cis*-2-enoic acid and formic acid, and this undergoes

¶ For the autoxidation of furan and its derivatives in the absence of photosensitisers, see Refs. 140 and 143–146.

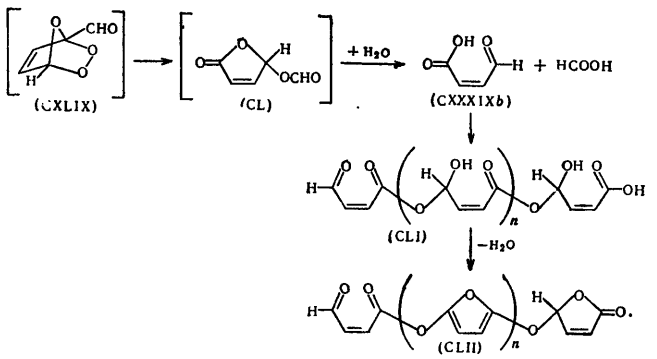
† Holeček and Horák[148] found that 4-oxopent-2-enoic acid (CXXXIX*a*) was formed by the photooxidation of 2-methylfuran in acetone medium in the presence of protoporphyrin IX.

alcoholysis to the pseudo-ester (CXLII*b*) and ethyl formate‡:



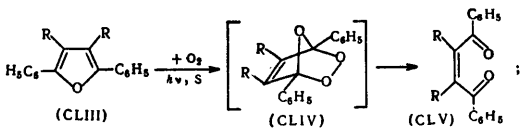
(CXLIX) (CL) (CXLII *b*)

Dunlop[153,154] studied the autoxidation of furfuraldehyde, which on standing in the air darkens and acquires an acid reaction. The investigation showed that the autoxidation involves the formation of formic acid, 4-oxobut-2-enoic acid and its polymer, and small amounts of 2-furoic acid. Dunlop assumed the first stage of the reaction to be formation of a 2,5-adduct of ozonide structure (CXLIX), which hydrolysed with the production of formic acid and the unstable 4-oxobut-2-enoic acid (CXXXIX*b*), the latter being converted into the polymeric acids (CLI), and (CLII), responsible for the brown colour of oxidised furfuraldehyde:



(CXLIX) (CL) (CXXXIX*b*) (CLI) (CLII)

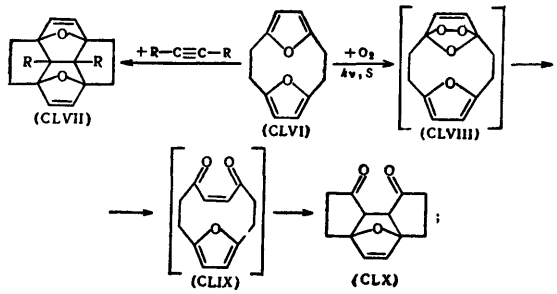
Martel[155] reported that the photochemical oxidation of 2,5-diphenylfuran (CLIII*a*) involves the formation of an unstable adduct of ozonide structure (CLIV*a*), which could not be isolated but whose structure was established by reduction with potassium iodide and acetic acid to 1,4-diphenylbut-*cis*-2-ene-1,4-dione (CLV*a*).



(CLIII) (CLIV) (CLV)

(*a*) R = H; (*b*) R = C_6H_5.

Martel[155], Wasserman[156], and Lutz[157] found that the photooxidation of 2,3,4,5-tetraphenylfuran (CLIII*b*) was accompanied by the formation of an unstable peroxide (CLIV*b*), which was reduced with potassium iodide and acetic acid to 1,2,3,4-tetraphenylbut-*cis*-2-ene-1,4-dione (CLV*b*).



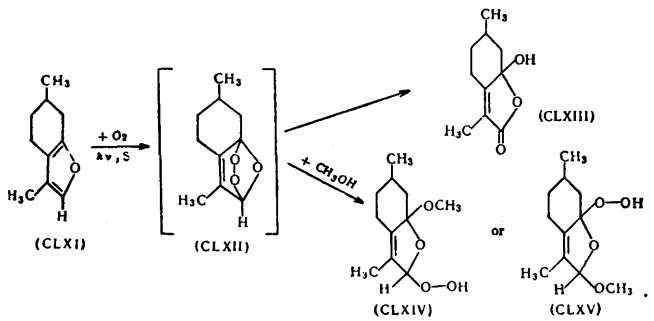
(CLVII) (CLVI) (CLVIII) (CLIX) (CLX)

R = $-COOCH_3$.

Cram[158] has shown that 1,4 : 7,10-diepoxydodeca-1,3,7,9-tetraene (CLVI) reacts with dimethyl acetylenedicarboxylate by a mechanism of diene synthesis to form an adduct (CLVII), whose configuration was not established.

Wasserman[159] established that the photosensitised oxidation of the heterocyclophane (CLVI) in alcoholic solution yields a 1,4-diketone (CLX), the reaction probably occurring in three stages: (i) oxidation of (CLVI) to the monoepidioxide (CLVIII); (ii) reduction of (CLVIII) to an unsaturated 1,4-diketone (CLIX); (iii) intramolecular diene condensation of (CLIX) to (CLX).

In 1958 Schenck and Foote[160] found that the photosensitised oxidation of menthofuran (CLXI) gives a 40% yield of the pseudo-acid (CLXIII). The unstable diene adduct of ozonide structure (CLXII) formed as an intermediate in this reaction could not be isolated even when the experiment was carried out at -20°§.



(CLXI) (CLXII) (CLXIII) (CLXIV) (CLXV)

The photooxidation of menthofuran in methanol medium gave an addition product of a methanol molecule to the epidioxide (CLXII), whose structure was not established. In 1964 Foote[147] reported that the product of the methanolysis of the epidioxide (CLXII) was a hydroperoxide (CLXIV) or (CLXV).

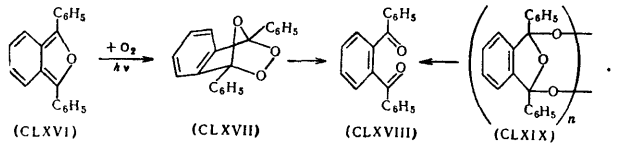
In 1946 Dufraisse[162] showed that, when dilute solutions of 1,3-diphenylisobenzofuran (CLXVI)¶ undergo photooxidation at -40°, an extremely unstable diene adduct of ozonide structure (CLXVII), which explodes at ~18°, is

‡ Schenck[149,150], Ogura[151], and Alder[152] have worked out a method for preparing the pseudo-ester (CXLII*b*) from furfuraldehyde.

§ In 1950 Woodward[161] had investigated the autoxidation of menthofuran, and isolated a 15% yield of the pseudo-acid (CLXIII) from the oxidation products.

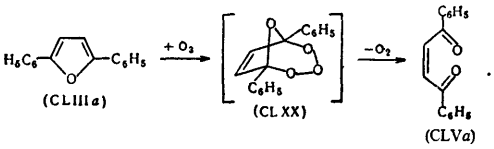
¶ 1,3-Diphenylisobenzofuran, which contains a reactive aromatic 1,3-diene system (*o*-quinoid grouping), readily undergoes diene condensation with maleic anhydride, acrylaldehyde, *p*-benzoquinone, and other dienophiles[163].

formed. In solution this adduct is rapidly converted at room temperature into *o*-dibenzoylbenzene (CLXVIII). In 1963 Le Berre[164] shook a benzene solution of 1,3-diphenylisobenzofuran (CLXVI) in an atmosphere of oxygen in the dark, and obtained a polymeric peroxide (CLXIX), which decomposed explosively when heated above 100°; quinol inhibits the autoxidation of 1,3-diphenylisobenzofuran. When the polyperoxide (CLXIX) was reduced with potassium iodide and and acetic acid, *o*-dibenzoylbenzene (CLXVIII) was obtained†.



(CLXVI) (CLXVII) (CLXVIII) (CLXIX)

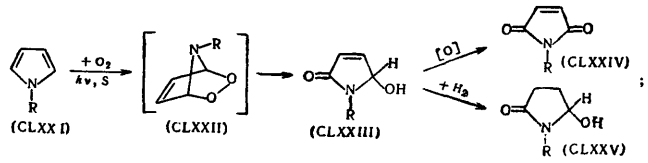
It was established in 1957 that[166] the ozonisation of 2,5-diphenylfuran (CLIII*a*) in acetone or methanol at -40° involves the formation of 1,4-diphenylbut-*cis*-2-ene-1,4-dione (CLV*a*). It is probable that in this case, too, the first stage in the process is 2,5 addition of an ozone molecule to 2,5-diphenylfuran to form the monoozonide (CLXX), the second stage being conversion of the O_3-adduct (CLXX) into *cis*-1,2-dibenzoylethylene (CLV*a*):



(CLIII*a*) (CLXX) (CLV*a*)

In 1939 Bernheim and Morgan[167] showed that illumination of an aqueous, alcoholic, or acetone solution of pyrrole in the presence of a photosensitiser (Methylene Blue, Eosin) and oxygen results in the formation of a crystalline substance melting at 102°. The structure of this substance was not determined.

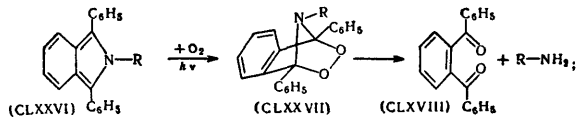
These experiments were repeated by de Mayo and Reid[168] in 1962, who found that, if a 0.1% aqueous solution of pyrrole (CLXXI*a*) was shaken with Eosin in an atmosphere of oxygen while exposed to a 100 W lamp, one molecular equivalent of oxygen was rapidly absorbed. A photooxidation product of composition $C_4H_5NO_2$ and m. p. 102° was isolated in 32% yield from the reaction mixture. Under the same conditions 1-methylpyrrole (CLXXI*b*) gave a 48% yield of a crystalline substance $C_5H_7NO_2$ melting at 85°. These workers assume that the photosensitised oxidation involves the initial formation of unstable diene adducts (CLXXII*a*) and (CLXXII*b*), which then rearrange to the compounds melting at 102° and 85°, for which the formulae (CLXXIII*a*) and (CLXXIII*b*) are proposed. These suggested structural formulae were confirmed by examination of the infrared spectrum of the substance melting at 102° and of the nuclear magnetic resonance spectrum of that melting at 85°. Oxidation of the photooxidation products (CLXXIII*a*) and (CLXXIII*b*) with active manganse dioxide gave respectively maleimide (CLXXIV*a*) and *N*-methylmaleimide (CLXXIV*b*), and catalytic hydrogenation of the photooxidation product of pyrrole (CLXXIII*a*) gave the dihydro-derivative (CLXXV*a*).



(CLXX I) (CLXXII) (CLXXIII) (CLXXIV) (CLXXV)

(*a*) R = H; (*b*) R = CH_3.

During 1955–1957 Theilacker and Schmidt[169] studied the oxidation of several derivatives of isoindole, and found that 2-methyl-1,3-diphenylisoindole (CLXXVI*a*) readily forms a diene adduct with maleic anhydride‡. Passage of a stream of air through a boiling solution of 2-methyl-1,3-diphenylisoindole (CLXXVI*a*) in aqueous butanol produced *o*-dibenzoylbenzene (CLXVIII). These workers assume the intermediate formation of an epidioxide (CLXXVII*a*), which is then hydrolysed with the formation of *o*-dibenzoylbenzene, methylamine, and hydrogen peroxide.

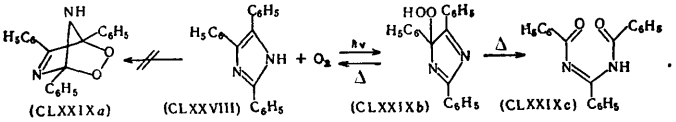


(CLXXVI) (CLXXVII) (CLXVIII)

(*a*) R = CH_3; (*b*) R = C_6H_5.

The photooxidation of dilute carbon-disulphide solutions of 1,2,3-triphenylisoindole (CLXXVI*b*), which is the nitrogen analogue of 1,3-diphenylisobenzofuran (CLXVI), gives a good yield of a diene adduct (CLXXVII*b*), which decomposes at 80–90°. Reduction of the adduct (CLXXVII*b*) with zinc and acetic acid produced a high yield of 1,2,3-triphenylisoindole (CLXXVI*b*), whereas reduction of (CLXXVII*b*) with sodium sulphite gave *o*-dibenzoylbenzene and aniline.

In 1957 Dufraisse[170–172] reported that the photooxidation of dilute solutions of lophine, 2,4,5-triphenylimidazole (CLXXVIII), in carbon disulphide at 18° involves the formation of a crystalline peroxide, which when heated to 170° decomposes into lophine (CLXXVIII), oxygen, and *NN'*-dibenzoylbenzamidine (CLXXIX*c*). He assumed the lophine peroxide which he had obtained to be a diene adduct (CLXXIX*a*), but an examination of its ultraviolet, infrared, and nuclear magnetic resonance spectra undertaken in 1964 has shown that it is a hydroperoxide (CLXXIX*b*)[173,174].



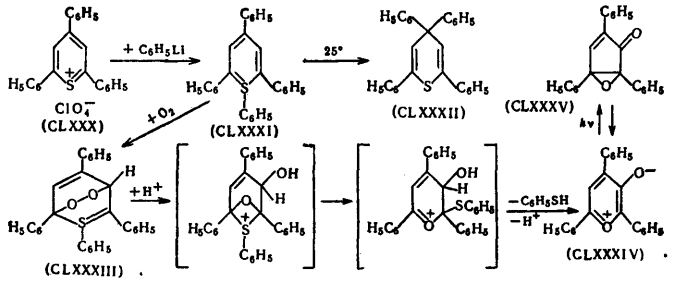
(CLXXIX*a*) (CLXXVIII) (CLXXIX*b*) (CLXXIX*c*)

In 1962 Suld and Price[175] reported that phenyllithium reacts in ether with 2,4,6-triphenylthiapyrylium perchlorate (CLXXX) to form the unstable 1,2,4,6-tetraphenylthiabenzene (CLXXXI), which was isolated as an ether complex, a purple amorphous mass. At room temperature (CLXXXI) isomerises to the colourless crystalline 2,4,4,6-tetraphenylthiapyran (CLXXXII). If oxygen is admitted to the reddish violet ethereal solution of tetraphenylthiabenzene (CLXXXI), the solution is rapidly decolorised with formation of an extremely unstable "transannular epidioxide" of 1,2,4,6-tetraphenylthiabenzene

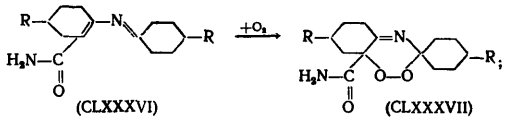
† As early as 1906 Guiot and Catel[165] had observed the formation of *o*-dibenzoylbenzene when benzene or alcoholic solutions of 1,3-diphenylisobenzofuran were in contact with air. They also noted that the oxidation of 1,3-diphenylisobenzofuran is more rapid in the light than in the dark.

‡ For diene syntheses with isoindoles, see Ref. 163, p. 554.

(CLXXXIII), which could not be isolated. In ethereal solution the "epidioxide" (CLXXXIII) reacts rapidly with hydrogen chloride to form benzenethiol and 2,4,6-triphenylpyrylium 3-oxide (CLXXXIV), consisting of dark red crystals. In 1963 Ullman[176] showed that, when an acetonitrile solution of (CLXXXIV) is illuminated, the latter undergoes reversible photochemical conversion into a valency tautomer, 4,5-epoxy-2,4,5-triphenylcyclopent-2-en-1-one (CLXXXV)§.



During 1961–1964 McKay[178–180] investigated the condensation of alicyclic ketones with urea. It was found that, when the latter was heated with cyclohexanone, 4-methylcyclohexanone, and 4-t-butylcyclohexanone, the corresponding condensation products (CLXXXVI*a–c*) were formed. In the purfication of these products it was noted that they absorbed oxygen very readily. One molecular equivalent of oxygen was absorbed when chloroform solutions of (CLXXXVI*a–c*) were stirred at room temperature and normal pressure in an atmosphere of pure oxygen for 1 h, and in the presence of 0.1% of cobalt naphthenate this occurred within 5 min. The oxidation products were crystalline peroxides, which were shown to have the structures (CLXXXVII*a–c*). Hence they had been formed by 1,4 addition of oxygen to the conjugated "diene" system of the condensation products (CLXXXVI*a–c*).



(*a*) R = H; (*b*) R = CH_3; (*c*) R = $(CH_3)_3C$.

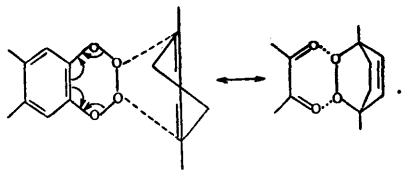
V. MECHANISM OF PHOTOSENSITISED OXIDATION; OXIDATION WITH SINGLET OXYGEN

On absorbing radiation, molecules pass into an excited electronic state, from which they return to the normal state with the emission of radiation (fluorescence). This excitation energy can be used for chemical reactions. The excited molecule can either react with a molecule which collides with it, or else transmit its energy to another molecule, which will then become a centre for photochemical reaction. In the latter case the molecule which absorbs the radiation acts solely as a sensitiser, and undergoes no change during the reaction (sensitised photochemical reaction)[181]. The problem of the nature of the intermediate products in the photosensitised oxidation of olefins and conjugated dienes has been discussed by several investigators.

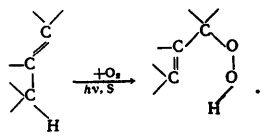
According to the ideas developed by Schönberg[182,183], Schenck[38,40,184–188], and Bowen[189,190], a sensitiser (S), on absorbing light energy, passes into a diradical (.S.), which adds on a molecule of oxygen to form a peroxy-radical (.S–O–O.). The labile oxygen in the peroxy-radical is then transferred to an acceptor A with formation of the peroxide AO_2 and the original sensitiser. Schönberg[183] assumes that the transfer of oxygen to the acceptor takes place either in a reaction aggregate or by breakdown of the peroxy-radical into the original sensitiser and active (nascent) oxygen.

$$S \xrightarrow{h\nu} {}^{\cdot}S^{\cdot},$$
$$^{\cdot}S^{\cdot} + O_2 \rightarrow {}^{\cdot}S{-}O{-}O^{\cdot}$$
$$^{\cdot}S{-}O{-}O^{\cdot} + A \rightarrow AO_2 + S.$$

On the basis of Schenck's concepts, Schuller et al.[107] suggested that in the case of the photosensitised oxidation of laevopimaric acid (CII) and palustric acid (CVI) (see Section II, 7) the transition state can be represented (with *o*-benzoquinone as sensitiser) as follows

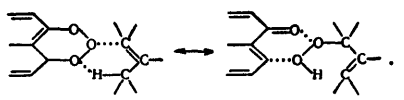


Schenck[35,38,184,191–200] and other workers[201–203] have established that the photosensitised oxidation of olefins involves migration of an allyl hydrogen atom to the oxygen with displacement of the double bond to a neighbouring position, i.e. by a mechanism of monoene addition. The reaction products are allyl hydroperoxides (CLXXXVIII)¶:



(CLXXXVIII)

Thus the first stage in the photosensitised oxidation of *p*-mentha-1,4(8)-diene (XXVIII) and neoabietic acid (CVIII) is their conversion into the allyl hydroperoxide (XXIX) and (CIX) (see Sections II, 4 and II, 7). Schuller and Lawrence[105,106] assume that in this case the transition state can be represented (with a 1,4-naphthaquinone derivative as sensitiser)



A different reaction mechanism was suggested for photosensitised oxidation by Kautsky[204–206], who regarded the oxidation as caused by photoactive oxygen. According to him the sensitised oxidation comprises two stages — light and dark: the light energy absorbed by a sensitiser

§ In 1964 Dunston and Yates[177] established that 4, 5-epoxy-2,3,4,5-tetraphenylcyclopent-2-en-1-one and 2,4,5,6-tetraphenylpyrylium 3-oxide are also photochemical valency tautomers.

¶ In the case of fused cyclic systems, the reaction occurs stereospecifically; it is the quasi-axial allyl hydrogen atom located in the *cis* position with respect to the newly formed C–O bond which migrates.

molecule is first transferred to an oxygen molecule; and in the second stage, for which illumination is not required, the excited oxygen molecule reacts, in one of two theoretically possible metastable singlet states $^1\Delta_g$ or $^1\Sigma_g$, with the acceptor A to form a peroxide product AO_2:

$$S \xrightarrow{h\nu} S^*,$$
$$S^* + O_2 \rightarrow O_2^* + S,$$
$$O^*_2 + A \rightarrow AO_2.$$

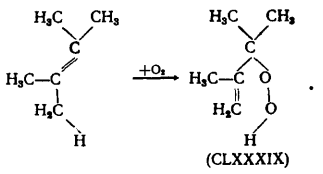
As an experimental demonstration of the correctness of his suggested reaction mechanism for photosensitised oxidation, Kautsky prepared separately peroxides of the sensitiser (Trypaflavine) and of the acceptor (the leuco base of Malachite Green), and illuminated mixtures of the two adsorbates (the experiments were carried out at low oxygen pressures). Under these conditions the leuco base was oxidised to the dye. This result provided a convincing proof of the correctness of Kautsky's suggested reaction mechanism.

A similar phenomenon has been observed by Rosenberg[207] in a study of the interaction of oxygen with photoexcited Acriflavine deposited on silica gel.

In 1964 Foote[147] and Corey[208] simultaneously published brief communications describing new methods for the oxidation of cyclic 1,3-dienes to transannular epidioxides with molecular oxygen in an excited singlet state.

Foote[147] obtained singlet oxygen *in situ* by the action of sodium hypochlorite on hydrogen peroxide. The technique of oxidation is very simple: to a solution in methanol of the substance to be oxidised are added 30% hydrogen peroxide, and then 1 M sodium hypochlorite solution with stirring and cooling. Foote's method is suitable for the preparation of epidioxides from cyclic 1,3-dienes and of allyl hydroperoxides from olefins. By the oxidation of cyclohexa-1,3-diene (XXI*c*) was obtained an epidioxide (XXII*c*, yield 20%) previously synthesised by Schenck (see Section II, 4). The oxidation of tetracyclone (LXIV*c*) gave 1,4-diphenylbut-*cis*-2-ene-1,4-dione (LXVI*c*, yield 50%), which had previously been obtained by the photooxidation of tetracyclone (see Section II, 5). The oxidation of 2,5-dimethylfuran (CXXXII*c*) in methanol gave a hydroperoxide (CXXXVI, yield 84%) identical with that obtained by Foote by the photosensitised oxidation of 2,5-dimethylfuran in methanol (see Section IV).

Foote reported that, according to preliminary results, rubrene and other acenes are also oxidised by singlet oxygen to transannular epidioxides. Oxidation of olefins containing allyl hydrogen atoms by means of singlet oxygen yields, with displacement of the double bond, allyl hydroperoxides. Thus the oxidation of 2,3-dimethylbut-2-ene led to 3-hydroperoxy-2,3-dimethylbut-1-ene (CLXXXIX, yield 63%), previously obtained by Schenck[196] by the photosensitised oxidation of 2,3-dimethylbut-2-ene.



(CLXXXIX)

Foote[209] regards his results as indicating that singlet oxygen may be the reactive intermediate in the photosensitised oxidation, too.

Corey[208] has employed the method of transforming molecular oxygen to the singlet state by means of an electric discharge, first described in 1956 by Foner and Hudson[210]. By this method ~10% of the molecular oxygen is converted to the $^1\Delta_g$ metastable state, and only ~0.01% passes into the $^1\Sigma_g$ metastable state. Corey carried out the oxidation of 1,3-dienes at 0° in bromobenzene, chlorobenzene, nitrobenzene, and other solvents. The oxidation of *p*-mentha-1,3-diene resulted in ascaridole (I), previously synthesised by Schenck (see Section II, 3). By the oxidation of 1,3-diphenylisobenzofuran (CLXVI) a high yield of *o*-dibenzoylbenzene (CLXVIII) was obtained. 9,10-Diphenylanthracene (CXIV*a*), anthracene (CXVII*a*), and 9,10-dimethylanthracene (CXVII*d*) were converted into the corresponding epidioxides (CXV*a*), (CXVIII*a*), and (CXVIII*d*), identical with specimens obtained by the photooxidation of these hydrocarbons (see Section III).

Attempts to oxidise 2,3-dimethylbut-2-ene, cyclohex-1-enylbenzene, pin-2-ene, and cholest-4-en-3β-ol to allyl hydroperoxides did not give positive results.

Corey's method cannot yet be employed to prepare transannular epidioxides from cyclic 1,3-dienes. The generator of metastable oxygen which he used enabled only a few millimoles of substances to be oxidised: for example, the oxidation of 100 mg of 9,10-dimethylanthracene to the 9,10-epidioxide lasted 19 h.

NOTE ADDED IN PROOF

Foote[212] has recently made a comparative stereochemical study of the reaction of *p*-mentha-1,8-diene with singlet oxygen and of the photosensitised oxidation of this compound. The results show that identical intermediates are formed in the two cases. Thus Foote's earlier suggestion[209], that singlet oxygen is formed as intermediate in the photooxidation of alkenes and dienoid compounds, has been confirmed experimentally.

1. Berichte von Schimmel und Co., 108 (April 1908); Chem. Zentr., I, 1839 (1908).
2. O. Wallach, Nachr. K. Ges. Wiss. Göttingen, 422 (1912).
3. O. Wallach, Annalen, 392, 59 (1912).
4. K. Bodendorf, Arch. Pharm., 271, 1 (1933).
5. G. O. Schenck, K. G. Kinkel, and H. J. Mertens, Annalen, 584, 125 (1953).
6. M. Matic and D. A. Sutton, J. Chem. Soc., 349 (1953).
7. E. K. Nelson, J. Amer. Chem. Soc., 33, 1404 (1911); 35, 84 (1913).
8. T. A. Henry and H. Paget, J. Chem. Soc., 119, 1714 (1921).
9. G. Jacob and G. Ourisson, Bull. Soc. chim. France, 734 (1958).
10. H. Thomas and W. Dobke, Arch. Pharm., 268, 128 (1930).
11. A. S. Danilova and G. V. Pigulevskii, Zhur. Obshch. Khim., 33, 2076 (1963).
12. A. S. Danilova, Zhur. Org. Khim., 1, 521 (1965).
13. D. A. Scott, Chem. Eng. News, 18, 404 (1940).
14. C. T. Handy and H. S. Rothrock, J. Amer. Chem. Soc., 80, 5306 (1958).
15. W. Kern and A. R. Heinz, Makromol. Chem., 16, 81 (1955).
16. W. Kern, K. Jockusch, and A. Wolfrom, Makromol. Chem., 3, 223 (1949).
17. A. L. Klebanskii and R. M. Sorokina, Zhur. Prikl. Khim., 35, 2735 (1962).
18. W. Kern and J. Stallmann, Makromol. Chem., 7, 199 (1951).
19. W. Kern, A. R. Heinz, and J. Stallmann, Makromol. Chem., 16, 21 (1955).

20. F. K. Kawahara, J. Amer. Chem. Soc., 79, 1447 (1957).
21. R. Jacquemain, Compt. rend., 215, 200 (1942).
22. S. H. Harper, H. W. B. Reed, and R. A. Thompson, J. Sci. Food Agric., 2, 94 (1951).
23. K. Griesbaum, A. A. Oswald, and W. Naegele, J. Org. Chem., 29, 1887 (1964).
24. B. A. Arbuzov, Zhur. Obshch. Khim., 3, 28 (1933).
25. V. M. Nikitin, Zhur. Obshch. Khim., 11, 209 (1948).
26. L. Desalbres, Bull. Soc. chim. France, 1245 (1950).
27. G. L. Dranishnikov, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 470 (1953).
28. L. Desalbres, B. Lahourcade, and J. Rache, Bull. Soc. chim. France, 761 (1956).
29. H. Hock and F. Depke, Chem. Ber., 84, 349 (1951).
30. H. Hock and F. Depke, Angew. Chem., 63, 243 (1951).
31. E. H. Farmer, Trans. Faraday Soc., 21, 122 (1946).
32. H. Hock and M. Siebert, Chem. Ber., 87, 554 (1956).
33. W. Kern, A. R. Heinz, and D. Höhr, Makromol. Chem., 18–19, 406 (1956).
34. G. O. Schenck and K. Ziegler, Naturwiss., 32, 157 (1944).
35. G. O. Schenck, Angew. Chem., 64, 12 (1952).
36. Schering AG., German P. 752 437 (1941); Chem. Zentr., 11 048 (1955).
37. G. O. Schenck and D. E. Dunlap, Angew. Chem., 68, 248 (1956).
38. G. O. Schenck, Angew. Chem., 69, 579 (1957).
39. G. O. Schenck, W. Müller, and H. Pfenning, Naturwiss., 41, 374 (1954).
40. G. O. Schenck, Naturwiss., 41, 452 (1954).
41. G. O. Schenck, E. Koerner, V. Gustorf, and H. Köller, Angew. Chem., 73, 707 (1961).
42. G. O. Schenck, German P. 913 892 (1954); Chem. Abs., 52, 14 704 (1958).
43. A. C. Cope, T. A. Liss, and G. W. Wood, J. Amer. Chem. Soc., 79, 6287 (1957).
44. J. Rigaudy and P. Courtot, Tetrahedron Letters, 95 (1961).
45. P. Courtot, Ann. Chim. (France), [13], 8, 197 (1963).
46. G. O. Schenck and H. Ziegler, Naturwiss., 38, 356 (1951).
47. G. O. Schenck and R. Wirtz, Naturwiss., 40, 581 (1953).
48. G. R. Evanege, W. Bergmann, and J. English, J. Org. Chem., 27, 13 (1962).
49. C. Dufraisse, G. Rio, and J.-J. Basslier, Compt. rend., 246, 1640 (1958).
50. C. Dufraisse, A. Étienne, and J.-J. Basselier, Compt. rend., 244, 2209 (1957).
51. R. Criegee, Angew. Chem., 74, 703 (1962).
52. R. Criegee, W.-D. Wirth, W. Engel, and H. A. Brune, Chem. Ber., 96, 2230 (1963).
53. T. G. Halsall, W. J. Rodewald, and D. Willis, Proc. Chem. Soc., 231 (1958).
54. T. G. Halsall, W. J. Rodewald, and D. Willis, J. Chem. Soc., 2798 (1959).
55. W. Dilthey, S. Henkels, and M. Leonhard, J. prakt. Chem., 151, 97 (1938).
56. G. O. Schenck, Z. Elektrochem., 56, 855 (1952).
57. C. Dufraisse, A. Étienne, and J. Aubry, Compt. rend., 239, 1170 (1954).
58. C. Dufraisse, A. Étienne, and J. Aubry, Bull. Soc. chim. France, 1201 (1954).
59. N. M. Bikales and E. I. Becker, J. Org. Chem., 21, 1405 (1956).
60. C. F. Wilcox and M. P. Stevens, J. Amer. Chem. Soc., 84, 1258 (1962).
61. C. F. H. Allen and J. A. Van Allan, J. Org. Chem., 18, 882 (1953).
62. Ya. K. Syrkin and I. I. Moiseev, Uspekhi Khim., 29, 442 (1960) [Russ. Chem. Rev., 201 (1960)].
63. G. Rio and A. Ranjon, Compt. rend., 248, 111 (1959).
64. A. Windaus and J. Brunken, Annalen, 460, 225 (1928).
65. A. Windaus and O. Linsert, Annalan, 465, 157 (1928).
66. A. Windaus, W. Bergmann, and A. Lüttringhaus, Annalen, 472, 195 (1929).
67. M. Müller, Z. physiol. Chem., 231, 75 (1931).
68. A. Windaus and R. Langer, Annalen, 508, 105 (1934).
69. G. D. Laubach, E. C. Schreiber, E. J. Agnello, E. N. Lightfoot, and K. J. Brunings, J. Amer. Chem. Soc., 75, 1514 (1953).
70. G. D. Laubach, E. C. Schreiber, E. J. Agnello, and K. J. Brunings, J. Amer. Chem. Soc., 78, 4746 (1956).
71. G. D. Laubach, U. S. P. 2 877 221 (1959).
72. G. D. Laubach, U. S. P. 2 897 128 (1959).
73. P. Bladon and T. Sleigh, Proc. Chem. Soc., 183 (1962).
74. P. Bladon, J. Chem. Soc., 2176 (1955).
75. F. Schenck, K. Buchholz, and O. Wiese, Ber., 69, 2696 (1936).
76. K. Hsude, J. Suzuki, and S. Ivasaki, Chem. Pharm. Bull. (Tokyo), 11, 405 (1963).
77. D. Dvornik, M. Kraml, and J. F. Bagli, J. Amer. Chem. Soc., 86, 2739 (1964).
78. A. Butenandt and H. Kudszus, Z. physiol. Chem., 253, 224 (1938).
79. E. L. Skau and W. Bergmann, J. Amer. Chem. Soc., 60, 986 (1938).
80. E. L. Skau and W. Bergmann, J. Org. Chem., 3, 166 (1938).
81. H. B. Henbest and R. A. L. Wilson, Chem. and Ind., 86 (1956).
82. A. Butenandt and J. Paland, Ber., 72, 424 (1939).
83. A. Windaus, E. Auchagen, W. Bergmann, and H. Butte, Annalen, 477, 268 (1930).
84. L. F. Fieser, Experientia, 6, 312 (1950).
85. L. F. Fieser and M. Fieser, "Steroids", Reinhold, New York, 1959, pp. 14, 98.
86. P. Bladon, R. B Clayton, C. W. Greenhalgh, H. B. Henbest, E. R. H. Jones, B. J. Lovell, G. Silverstone, G. W. Wood, and G. F. Woods, J. Chem. Soc., 4883 (1952).
87. P. Bladon, H. B. Henbest, E. R. H. Jones, G. W. Wood, and G. F. Woods, J. Chem. Soc., 4890 (1952).
88. P. Bladon, H. B. Henbest, E. R. H. Jones, G. W. Wood, D. C. Eaton, and A. A. Wagland, J. Chem. Soc., 2916 (1953).
89. P. Bladon, H. B. Henbest, E. R. H. Jones, B. J. Lovell, and G. F. Woods, J. Chem. Soc., 125 (1954).
90. T. Achtermann, Z. physiol. Chem., 217, 281 (1933).
91. J. L. Dunn, I. M. Heilbron, R. F. Phipers, K. M. Samant, and F. S. Spring, J. Chem. Soc., 1576 (1934).
92. L. F. Fieser, "The Chemistry of Natural Products Related to Phenanthrene", Reinhold, New York, 1936, p. 174.
93. W. Bergmann, F. B. Hirschmann, and E. L. Skau, J. Org. Chem., 4, 29 (1939).
94. R. B. Clayton, H. B. Henbest, and E. R. H. Jones, J. Chem. Soc., 2015 (1953).
95. P. Wieland and V. Prelog, Helv. Chim. Acta, 30, 1028 (1947).
96. G. Bauslaugh, G. Just, and F. Blank, Nature, 202, 1218 (1964).
97. R. J. Conca and W. Bergmann, J. Org. Chem., 18, 1104 (1953).
98. E. J. Agnello, R. Pinson, and G. D. Laubach, J. Amer. Chem. Soc., 78, 4756 (1956).
99. D. Dvornik, M. Kraml, J. Dubuc, M. Givner, and R. Gaudry, J. Amer. Chem. Soc., 85, 3309 (1963).
100. G. A. Blondin, B. D. Kulkarni, and W. R. Nes, J. Amer. Chem. Soc., 86, 2528 (1964).
101. R. N. Moore and R. V. Lawrence, J. Amer. Chem. Soc., 80, 1438 (1958); 81, 458 (1959).
102. R. N. Moore and R. V. Lawrence, U. S. P. 2 899 463 (1959).
103. R. N. Moore and R. V. Lawrence, U. S. P. 2 996 515 (1961).
104. W. H. Schuller, J. C. Minor, and R. V. Lawrence, Ind. Eng. Chem., Prod., Res. Develop., 3, 97 (1964).
105. W. H. Schuller and R. V. Lawrence, Chem. and Ind., 105 (1961).

106. W. H. Schuller and R. V. Lawrence, J. Amer. Chem. Soc., 83, 2563 (1961).
107. W. H. Schuller, R. N. Moore, and R. V. Lawrence, J. Amer. Chem. Soc., 82, 1734 (1960).
108. C. Moureu, C. Dufraisse, and P. M. Dean, Compt. rend., 182, 1440, 1584 (1926).
109. C. Dufraisse, Bull. Soc. chim. France, [5], 3, 1857 (1936).
110. C. F. H. Allen and L. Gilman, J. Amer. Chem. Soc., 58, 937 (1936).
111. A. Willemart, "Groupe du Naphtacene et du Rubrene", in V. Grignard, G. Dupont, and R. Locquin, "Traité de Chimie organique", Vol. 17, Masson, Paris, 1949, p. 1270.
112. C. Dufraisse and J. Houpillart, Compt. rend., 205, 740 (1937).
113. C. Dufraisse and M. Badoche, Compt. rend., 193, 63 (1931).
114. C. Dufraisse and A. Étienne, Compt. rend., 201, 280 (1935).
115. C. Dufraisse and J. Le Bras, Bull. Soc. chim. France, [5], 4, 349 (1937).
116. C. Dufraisse and L. Velluz, Compt. rend., 208, 1822 (1939).
117. C. Dufraisse and L. Velluz, Bull. Soc. chim. France, [5], 9, 171 (1942).
118. C. Dufraisse and M. Gergard, Compt. rend., 201, 428 (1935); 202, 1859 (1936).
119. C. Dufraisse and M. Gergard, Bull. Soc. chim. France, [5] 4, 2052 (1937).
120. A. Willemart, Compt. rend., 205, 866 (1937).
121. A. Willemart, Bull. Soc. chim. France, [5], 5, 556 (1938).
122. A. Mustafa, Chem. Rev., 51, 18 (1952).
123. C. Dufraisse, Bull. Soc. chim. France, [5], 6, 422 (1939).
124. W. Bergmann and M. J. McLean, Chem. Rev., 28, 367 (1941).
125. A. Étienne, "Photo-oxydes d'Acènes. Union labile de l'Oxygène au Carbone" in V. Grignard, G. Dupont, and R. Locquin, "Traité de Chimie organique", Vol. 17, Masson, Paris, 1949, p. 1299.
126. E. G. E. Hawkins, "Organic Peroxides", Spon, London, 1961, p. 236.
127. C. Dufraisse and R. Priou, Bull. Soc. chim. France, [5], 5, 611 (1938).
128. C. Dufraisse and J. Houpillart, Bull. Soc. chim. France, [5], 5, 626 (1938).
129. C. Dufraisse and M. Badosche, Compt. rent., 200, 929, 1103 (1935).
130. C. Pinazzi, Compt. rend., 225, 1012 (1947).
131. C. Pinazzi, Compt. rend., 226, 929 (1948).
132. R. Criegee, "Herstellung und Umwandlung von Peroxyden" in Houben–Weyl, "Methoden der organischen Chemie", 4th Edn., Vol. 8, Part 3, Georg Thieme, Stuttgart, 1952, p. 61.
133. P. de Bruyn, Bull. Soc. chim. belges, 69, 328 (1960).
134. R. E. Erickson, P. S. Bailey, and J. C. Davis, Tetrahedron, 18, 389 (1962).
135. E. J. Moriconi and L. B. Taranko, J. Org. Chem., 28, 2526 (1963).
136. M. Avram, D. Dinu, and C. D. Nenitzescu, Chem. and Ind., 257 (1959).
137. M. Avram, D. Dinu, G. Mateescu, and C. D. Nenitzescu, Chem. Ber., 93, 1789 (1960).
138. M. Avram, J. G. Dinulescu, D. Dinu, G. Mateescu, and C. D. Nenitzescu, Tetrahedron, 19, 309 (1963).
139. M. P. Cava and R. Pohlke, J. Org. Chem., 28, 1012 (1963).
140. G. O. Schenck, Annalen, 584, 156 (1953).
141. G. O. Schenck, German P. 875 650 (1942); Chem. Zentr., 6345 (1954).
142. G. O. Schenck, German P. 881 193 (1941); Chem. Zentr., 5415 (1955).
143. G. O. Schenck, Naturwiss., 31, 387 (1943).
144. G. O. Schenck, Ber., 77, 661 (1944).
145. G. O. Schenck, Chem. Ber., 80, 289 (1947).
146. G. O. Schenck, Naturwiss., 35, 28 (1948).
147. C. Foote and S. Wexler, J. Amer. Chem. Soc., 86, 3879 (1964).
148. V. Holeček and V. Horák, Coll. Czech. Chem. Comm., 27, 2717 (1962).
149. FIAT Review of German Science 1939–1946. K. Ziegler (Editor), "Präparative organische Chemie", Part 2, Verlag Chemie, Weinheim, 1953, p. 195.
150. Houben–Weyl, "Methoden der organischen Chemie", 4th Edn., Vol. 8, Part 3, Georg Thieme, Stuttgart, 1952, p. 402.
151. I. Ogura, Jap. P. 6314 (1956); Chem. Abs., 52, 11 910 (1958).
152. K. Alder and F. Farina, Anales real Soc. españ. Fis. Quim., B 54, 689 (1958).
153. A. P. Dunlop, P. R. Stout, and S. Swadesh, Ind. Eng. Chem., 38, 705 (1946).
154. A. P. Dunlop, Ind. Eng. Chem., 40, 204 (1948).
155. J. Martel, Compt. rend., 244, 626 (1957).
156. H. H. Wasserman and A. Libertles, J. Amer. Chem. Soc., 82, 2086 (1960).
157. R. E. Lutz, W. J. Welstead, R. G. Bass, and J. J. Dale, J. Org. Chem., 27, 1111 (1962).
158. D. J. Cram and G. R. Knox, J. Amer. Chem. Soc., 83, 2204 (1961).
159. H. H. Wasserman and A. R. Doumaux, J. Amer. Chem. Soc., 84, 4611 (1962).
160. G. O. Schenck and C. Foote, Angew. Chem., 70, 505 (1958).
161. R. B. Woodward and R. H. Eastman, J. Amer. Chem. Soc., 72, 399 (1950).
162. C. Dufraisse and S. Ecary, Compt. rend., 223, 735 (1946).
163. A. S. Onishchenko, "Dienovyi Sintez" (Diene Synthesis), Izd. Akad. Nauk SSSR, Moscow, 1963, p. 544.
164. A. Le Berre and R. Ratsimbazafy, Bull. Soc. chim. France, 229 (1963).
165. A. Guiot and J. Catel, Bull. Soc. chim. France, 35, 1124 (1906).
166. P. S. Bailey and H. O. Colomb, J. Amer. Chem. Soc., 79, 4238 (1957).
167. F. Bernheim and J. E. Morgan, Nature, 144, 290 (1939).
168. P. de Mayo and S. T. Reid, Chem. and Ind., 1576 (1962).
169. W. Theilacker and W. Schmidt, Annalen, 597, 95 (1955); 605, 43 (1957).
170. C. Dufraisse, A. Étienne, and J. Martel, Compt. rend., 244, 970 (1957).
171. C. Dufraisse and J. Martel, Compt. rend., 244, 3106 (1957).
172. C. Dufraisse and J. Martel, Compt. rend., 245, 457 (1957).
173. J. Sonnenberg and D. M. White, J. Amer. Chem. Soc., 86, 5685 (1964).
174. E. H. White and M. J. C. Harding, J. Amer. Chem. Soc., 86, 5686 (1964).
175. G. Suld and C. C. Price, J. Amer. Chem. Soc., 84, 2094 (1962).
176. E. F. Ullman, J. Amer. Chem. Soc., 85, 3529 (1963).
177. J. M. Dunston and P. Yates, Tetrahedron Letters, 505 (1964).
178. A. F. McKay, E. J. Tarlton, and C. Podesva, J. Org. Chem., 26, 76 (1961).
179. A. F. McKay, C. Podesva, E. J. Tarlton, and J.-M. Billy, Canad. J. Chem., 42, 10 (1964).
180. A. F. McKay, J.-M. Billy, and E. J. Tarlton, J. Org. Chem., 29, 291 (1964).
181. G. Herzberg, "Molecular Spectra and Molecular Structure", Vol. 1, "Spectra of Diatomic Molecules", 2nd Edn., Van Nostrand, New York, 1950, p. 560.
182. A. Schönberg, Annalen, 518, 299 (1935).
183. A. Schönberg, "Präparative organische Photochemie" (Translated into Russian), Inostr. Lit., Moscow, 1963, p. 99.

184. G. O. Schenck, Naturwiss., 35, 28 (1948).
185. G. O. Schenck and K. G. Kinkel, Naturwiss., 38, 355, 503 (1951).
186. G. O. Schenck, Naturwiss., 40, 205, 229 (1953).
187. G. O. Schenck and E. Koch, Z. Elektrochem., 64, 170 (1960).
188. G. O. Schenck, Z. Elektrochem., 64, 997 (1960).
189. E. J. Bowen and D. W. Tanner, Trans. Faraday Soc., 51, 475 (1955).
190. E. J. Bowen, "The Photochemistry of Aromatic Hydrocarbon Solutions", in "Advances in Photochemistry", Vol. I, Interscience, New York, 1963, p. 23.
191. G. O. Schenck, H. Eggert, and W. Denk, Annalen, 584, 177 (1953).
192. G. O. Schenck, German P. 933 925 (1943); Chem. Zentr., 3998 (1956).
193. G. O. Schenck, K. Gollnick, and O. A. Neumüller, Annalen, 603, 46 (1957).
194. G. O. Schenck, O. A. Neumüller, and W. Eisfeld, Annalen, 618, 202 (1958).
195. G. O. Schenck and O. A. Neumüller, Annalen, 618, 194 (1958).
196. G. O. Schenck and K. H. Schulte-Elte, Annalen, 618, 185 (1958).
197. G. O. Schenck, S. Schroeter, and G. Ohloff, Chem. and Ind., 459 (1962).
198. G. O. Schenck, K. Gollnick, G. Buchwald, G. Ohloff, G. Schade, and S. Schroeter, Angew. Chem., 76, 582 (1964).
199. G. O. Schenck, K. Gollnick, G. Buchwald, S. Schroeter, and G. Ohloff, Annalen, 674, 93 (1964).
200. K. Gollnick and G. O. Schenck, Pure Appl. Chem., 9, 507 (1964).
201. A. Nickon and J. F. Bagli, J. Amer. Chem. Soc., 81, 6330 (1959); 83, 1498 (1961).
202. R. L. Kenney and G. S. Fischer, J. Amer. Chem. Soc., 81, 4288 (1959).
203. R. L. Kenney and G. S. Fischer, J. Org. Chem., 28, 3509 (1963).
204. H. Kautsky and H. de Bruijn, Naturwiss., 19, 1043 (1931).
205. H. Kautsky, H. de Bruijn, R. Neuwirth, and W. Baumeister, Ber., 66, 1588 (1933).
206. H. Kautsky, Biochem. Z., 291, 271 (1937).
207. J. L. Rosenberg and D. J. Shombert, J. Amer. Chem. Soc., 82, 3257 (1960).
208. J. Corey and W. C. Taylor, J. Amer. Chem. Soc., 86, 3881 (1964).
209. C. S. Foote and S. Wexler, J. Amer. Chem. Soc., 86, 3880 (1964).
210. S. N. Foner and R. L. Hudson, J. Chem. Phys., 25, 601 (1956).
211. G. Bernhardt and F. Korte, Angew. Chem., 77, 133 (1965).
212. Chem. Eng. News, 43, No. 16, 41 (1965).

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THE EXTRACTION OF HETEROPOLY-COMPOUNDS AND ITS APPLICATION IN INORGANIC ANALYSIS

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I. INTRODUCTION

In recent years, in the analytical determination of silicon, phosphorus, and arsenic, small quantities of which are most reliably determined by photometric measurements on their heteropoly-acids, increasing use has been made of the extraction of these heteropoly-acids by organic solvents.

The increasing introduction of the extraction method in the field of heteropoly-compounds cannot be attributed entirely to the general and nowadays widely known advantages of this method. Certain particular advantages of the extraction method are shown to a greater extent by heteropoly-compounds than by any other types of compounds. In this connection it is sufficient to mention two features.

A serious disadvantage of all analytical methods based on photometric measurements on molybdenum heteropoly-compounds (particularly their reduced blue forms) is the superposition of the light absorption of the reagent itself — molybdate; the use of extraction makes possible the ready and reliable elimination of the influence of molybdate, since isopolymolybdate, unlike heteropolymolybdates, is generally not extracted by organic solvents.

Another frequent obstacle to the analytical application of heteropoly-compounds is the instability of the light absorption of the solutions taken for the photometric measurements. This is due to the existence of complex equilibria in aqueous solutions of the heteropoly-compounds, which are extremely sensitive to very small changes in the conditions. The solutions obtained as a result of extraction of the heteropoly-compound by organic solvents are much more stable than the aqueous solutions.

The study of the extraction behaviour of heteropoly-compounds, apart from its analytical value[1-4], is also of undoubted interest from other viewpoints.

The most important method for the preparation of the heteropoly-acids of most elements is the ether method, based on separation of the heteropoly-acids from acidified solutions of their salts by means of diethyl ether[4].

Extraction may provide a valuable method for studying the physicochemical properties of heteropoly-compounds, for which reliable experimental methods are still urgently required[5].

The combination of the most varied properties in a single chemical individual, so characteristic of heteropoly-compounds, is a favourable factor in obtaining useful and concentrated information on the theory of extraction when these compounds are chosen as objects for study (models).