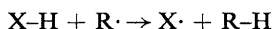


Hydrogen Abstraction in the Liquid Phase by Free Radicals

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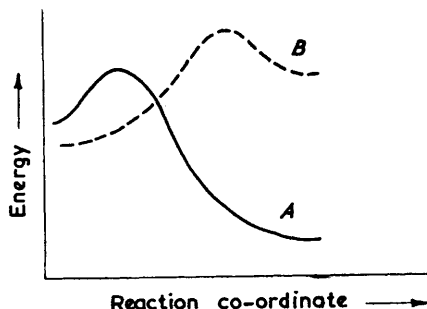
One of the most frequently encountered reactions of free radicals is that of hydrogen abstraction. The purpose of this Review is to draw together information on the abstraction of hydrogen from a variety of hydrogen-containing bonds in a variety of environments



General Principles

Bond Strengths.—The significance of the strength of the bond broken (X-H) and of the one formed (R-H) in the reaction has been considered in a previous Review.¹

Polar Effects.—On the basis of Hammonds' postulate² (see Figure) we can say that for a highly exothermic reaction (A) the transition state will resemble the reactants, *i.e.*, very little rupture of bond X-H will have occurred. For a less exothermic reaction (B) the transition state will bear more resemblance to the products, *i.e.*, more bond rupture will have occurred. From this consideration we would expect polar effects within the substrate molecule, which affect the stability of the incipient radical, to be more important in reactions of high



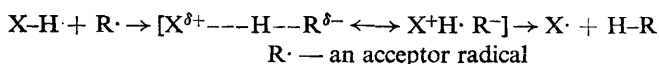
Energy diagram for the $\text{X-H} + \text{R}\cdot \rightarrow \text{X}\cdot + \text{H-R}$ reactions
A, Reaction with reactive free-radical
B, Reaction with stable free-radical

¹ J. M. Tedder, *Quart. Rev.*, 1960, 14, 336.

² G. S. Hammond, *J. Amer. Chem. Soc.*, 1955, 77, 334.

activation energy. This has been demonstrated in the abstraction of hydrogen from benzylic C-H bonds.³ The order of reactivity of C-H bonds has been found to be tertiary > secondary > primary.⁴ This difference in reactivity is dependent upon the difference in stability of their respective incipient radicals. It is not surprising therefore that a reactive radical (*e.g.*, Cl·, CH₃·) shows little discrimination between the different types of bond, whereas less reactive radicals (*e.g.*, Br·, ·CCl₃) show much greater selectivity in their attack.

In the course of attack upon a bond (X-H) by a radical (R·), electron transfer to or from the radical may occur and, to signify the preferred direction of movement, the terms acceptor and donor radicals have been suggested.⁵ The direction of the transfer depends on the relative stabilities of the R⁺ and R⁻ ions. Alkyl radicals are classed as donor radicals and in certain cases this has been verified experimentally.⁶ The donor property is to be expected from a consideration of the stability of carbonium ions relative to carbanions. The majority of radicals, halogen, alkoxy, peroxy, etc., have been found to behave as acceptor radicals. The preferred direction of electron transfer is particularly relevant to the type of polar structures which can be written as contributing to the transition state, *e.g.*



Substituents in the substrate molecule which favour the polar structures preferred by the attacking radical will obviously facilitate the reaction however little bond rupture has occurred in the transition state. Russell⁷ has determined the reactivity of a number of nuclear-substituted cumenes towards peroxy-radicals (reactive acceptor radicals), and has found that electron-releasing substituents (*e.g.*, alkyl groups) facilitate attack. Electron-attracting substituents (*e.g.*, halogen, nitro-, or cyano-groups) had a deactivating influence even though some of them can stabilise the incipient radical. Electron-releasing groups (*e.g.*, RO, R₂N) are particularly effective in activating a hydrogen atom attached to the same carbon atom as themselves since they can also stabilise the incipient radical by resonance. Electron-withdrawing groups, on the other hand, deactivate similar C-H bonds to attack by acceptor radicals since they do not favour the development of the required polar character in the transition state. Such an effect does not operate in reactions with donor radicals since the contributing polar structures to the transition state are of a different type. It has been shown, for instance, that the carboxyl group is particularly effective in deactivating adjacent C-H bonds towards chlorine radicals⁸ whereas no such effect is found⁹ in the reaction with methyl radicals. In some cases, the deactivating

³ R. F. Bridger and G. A. Russell, *J. Amer. Chem. Soc.*, 1963, **85**, 3754.

⁴ A. F. Trotman-Dickenson, *Quart. Rev.*, 1953, **7**, 198.

⁵ W. A. Waters, *Tetrahedron*, 1959, *Suppl. No. 3*, 151.

⁶ A. L. Buley and R. O. C. Norman, *Proc. Chem. Soc.*, 1964, 225.

⁷ G. A. Russell, *J. Amer. Chem. Soc.*, 1956, **78**, 1047.

⁸ C. Walling, 'Free Radicals in Solution', John Wiley and Sons, New York, 1957.

⁹ C. C. Price and H. Morita, *J. Amer. Chem. Soc.*, 1953, **75**, 3686.

influence of an electron-withdrawing substituent may be offset by its ability to stabilise the incipient radical. There is very little difference in the activation energies for the abstraction of hydrogen from methane and methyl chloride by chlorine radicals, whereas the reactions with methylene dichloride and chloroform show a large increase.¹ Thus, as the number of chlorine substituents increase, the deactivating influence increases relative to the stabilising effect.

Solvent Effects

This subject has been reviewed recently.¹⁰

Abstraction from Alkanes and Aralkanes

The reactions of these compounds with methyl, phenyl, t-butoxyl, peroxy,^{7,11} chlorine,¹¹ bromine, and trichloromethyl radicals¹² have been studied and many of the results collated in a recent paper.³ The attack upon the C-H bonds becomes more selective as the stability of the radical increased. The selectivity of the chlorine radical is¹³ unusually high in the reaction with aralkanes. This was found to be due to an interaction between the aromatic system and the radical. Extrapolation of the results obtained from reactions run at high dilution in inert solvents to infinite dilution overcame this effect and normal selectivity values were obtained. It has been shown¹⁴ that in the bromination of aralkanes, the reactivity of the C-H bonds is the same whether the source of radicals be *N*-bromosuccinimide or bromine. This has been taken as further evidence in support of the mechanism¹⁵ in which the bromine radical is the species which abstracts hydrogen.

Abstraction from Cyclic Alkanes

The reactivities of a number of cyclic alkanes towards methyl,¹⁶ phenyl,³ chlorine,¹⁷ trichloromethyl,¹⁸ and trichloromethylsulphonyl¹⁸ radicals have been determined. The order of reactivity was $C_6 < C_5 < C_7 < C_8$. In some cases very little difference in reactivity between cyclopentane and cyclohexane was detected.¹⁸ The order of reactivity parallels the stability of their respective cycloalkyl radicals which suggests that the amount of C-H bond rupture in the transition state allows some relief of ring strain. The reactivities of the cycloalkanes C_5 to C_3 towards t-butoxyl radicals decrease¹⁹ as the ring becomes

¹⁰ E. S. Huyser, *Adv. Free Radical Chem.*, 1965, **1**, 77.

¹¹ G. A. Russell and R. C. Williamson, jun., *J. Amer. Chem. Soc.*, 1964, **86**, 2357.

¹² (a) E. S. Huyser, *J. Amer. Chem. Soc.*, 1960, **82**, 394; (b) R. E. Pearson and J. C. Martin, *J. Amer. Chem. Soc.*, 1963, **85**, 3142.

¹³ G. A. Russell, A. Ito, and D. G. Hendry, *J. Amer. Chem. Soc.*, 1963, **85**, 2976.

¹⁴ C. Walling, A. Rieger, and D. D. Tanner, *J. Amer. Chem. Soc.*, 1963, **85**, 3129; see also

G. A. Russell and K. M. Desmond, *J. Amer. Chem. Soc.*, 1963, **85**, 3139.

¹⁵ J. Adam, P. A. Gosselain, and P. Goldfinger, *Nature*, 1953, **171**, 704; *Bull. Soc. chim. belges*, 1956, **65**, 523.

¹⁶ A. S. Gordon and S. R. Smith, *J. Phys. Chem.*, 1962, **66**, 521.

¹⁷ G. A. Russell, *J. Amer. Chem. Soc.*, 1958, **80**, 4997.

¹⁸ E. S. Huyser, H. Schimke, and R. L. Burham, *J. Org. Chem.*, 1963, **28**, 2141.

¹⁹ C. Walling and P. S. Fredricks, *J. Amer. Chem. Soc.*, 1962, **84**, 3326.

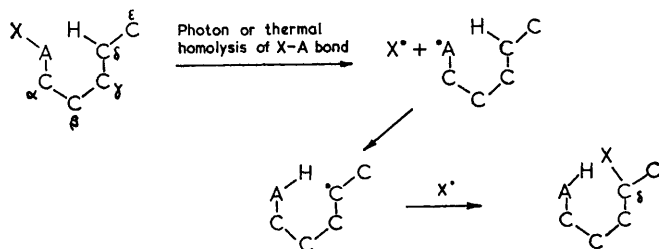
smaller. Cyclopropyl C-H bonds were particularly unreactive. It has been suggested that the high degree of 's-character' of the bonds does not favour the appropriate polar contributions to the transition state which an attack by an acceptor radical requires. The high reactivity of methyl groups attached to a cyclopropane ring is believed to be due to the ability of the ring to stabilise the incipient radical. The reactivity of bridgehead C-H bonds towards chlorine radicals has been investigated. These bonds are particularly unreactive in norbornane²⁰ but in bicyclo[2,2,2]octane²¹ they showed some reactivity. The difference in reactivity probably reflects the greater flexibility of the latter ring system which allows the development of ionic character in the transition state.

Abstraction from Cycloalkenes

The high degree of reactivity of allylic C-H bonds may be ascribed to the ability of the double bond to stabilise polar structure which contribute to the transition state and also the incipient radical. This stabilisation effect will be affected by the amount of orbital overlap between the double bond and the reaction centre. The amount of overlap in cycloalkenes will be regulated by the geometry of the ring system. The planar cyclopentene system, for instance, is much more reactive than the skewed cyclo-octene system.²² The reactivities of a number of cycloalkenes (C₅ to C₈) towards methyl,²³ phenyl,³ bromine,¹⁴ and peroxy-radicals²² have been determined and it was found that the order of reactivity varied according to the radical used. There has not been a satisfactory explanation for these observations.

Intramolecular Hydrogen Abstractions of Synthetical Importance

The Hofmann-Loeffler, Barton, and Related Reactions.—The essential steps of these reactions are shown in Scheme 1.



A = RNH⁺; X = Halogen; Hofmann-Loeffler reaction

A = O; X = Halogen, NO; Barton reaction

A = O; X = H; Lead tetra-acetate used to generate alkoxy radicals (ref. 24)

²⁰ E. C. Kooyman and G. C. Vegter, *Tetrahedron*, 1958, 4, 382.

²¹ A. F. Bickel, J. Knotnerus, E. C. Kooyman, and G. C. Vegter, *Tetrahedron*, 1960, 9, 230.

²² D. E. Van Sickle, F. R. Mayo, and R. M. Aluck, *J. Amer. Chem. Soc.*, 1965, 87, 4824.

²³ J. Gresser, A. Rajbenback, and M. Szwarc, *J. Amer. Chem. Soc.*, 1961, 83, 3005.

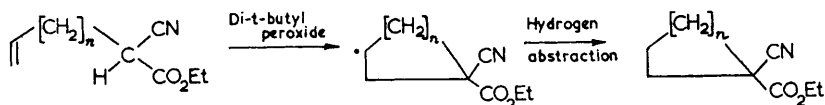
²⁴ K. Heusler and J. Kalvoda, *Angew. Chem. Internat. Edn.*, 1964, 3, 525.

The synthetical importance of the reactions lies in the fact that the substitution which is brought about at the δ carbon atom may be very difficult to obtain by other chemical methods. The specific attack at the δ carbon atom, is due to the necessity for a six-membered cyclic transition state. The steric requirements of the reaction have been reviewed.²⁴

The product of the Hofmann-Loeffler reaction, a δ -halogenoamine, has been found to cyclise readily under basic conditions to give pyrrolidine derivatives. The scope of the reaction has been reviewed.²⁵

The Barton reaction, which has been reviewed,²⁶ has been extensively used in the steroid field. Barton and his co-workers have illustrated the usefulness of the reaction in their brilliant syntheses of aldestosterone²⁷ and connessine.²⁸

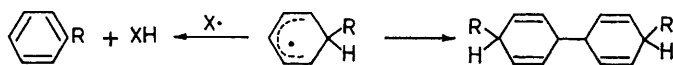
Radical Cyclisations.—Julia has recently reviewed²⁹ his work on the peroxide-initiated intramolecular cyclisation of ethylenic α -cyano-esters. The reaction has been employed to synthesise cyclopentane, cyclohexane, indane, decalin, and some tricyclic systems.



The propagation reaction is the abstraction of hydrogen from ester (a) by the radical (b).

Role of Hydrogen Abstraction in Homolytic Aromatic Substitution

The substituted cyclohexadienyl radical, which is an intermediate in homolytic aromatic substitution, may dimerise, disproportionate, or have a hydrogen atom abstracted by a radical, with formation of a substituted aromatic product



Scheme 2

(Scheme 2).³⁰ If the last reaction is relatively inefficient, the yield of dimerisation and disproportionation products is increased. For example, it has been observed³¹ in the reaction between amino-radicals and substituted benzenes, that the yields of tetrahydrobiaryls are high unless the substituents have strong electron-releas-

²⁵ M. E. Wolff, *Chem. Rev.*, 1963, 63, 55.

²⁶ M. Akhtar, *Adv. Photochem.*, 1964, 2, 263.

²⁷ D. H. R. Barton and J. M. Beaton, *J. Amer. Chem. Soc.*, 1960, 82, 2641.

²⁸ A. L. Nussbaum, F. E. Carlon, E. P. Oliveto, E. Townley, P. Kabasakalian, and D. H. R. Barton, *Tetrahedron*, 1962, 18, 373.

²⁹ M. Julia, *Rec. Chem. Progr.*, 1964, 25, 3.

³⁰ For a more detailed account see G. H. Williams 'Homolytic Aromatic Substitution', Pergamon Press, London, 1960.

³¹ F. Minisci, R. Galli, and M. Cecere, *Tetrahedron Letters*, 1965, No. 51, 4663.

ing properties which facilitate hydrogen abstraction by the acceptor amino-radicals. Bryce-Smith and his co-workers³² observed, in the reaction between phenyl radicals and isopropylbenzene, that the lower the concentration of radicals in the solution, the lower the yield of phenylated cumenes. An increased yield of the latter product is obtained when the concentration of radicals is increased which favours the hydrogen-abstraction process.

Hey and his co-workers,³³ in their detailed studies of the reactivity of substituted benzenes towards substituted phenyl radicals, found that electron-releasing substituents activate the molecule towards acceptor radicals and electron-withdrawing substituents favour attack by donor radicals. It was found,³⁴ for instance, in the reaction between substituted phenyl radicals and toluene, that substituents which increased the donor properties of the radical brought about an increased amount of hydrogen abstraction from the benzylic C-H bonds; *i.e.*, the electron-releasing properties of the methyl group deactivated the nucleus to attack by donor radicals.

Hydrogen Abstraction from Various Compounds: Carboxylic Acids and Derivatives.—There are a few examples of abstraction of hydrogen from a carboxyl group. Norman and his co-workers have shown,³⁵ by e.s.r. spectroscopy, that methyl radicals are produced in the reaction between hydroxyl radicals and acetic acid. It has been suggested that the methyl radicals were formed by decarboxylation of acetoxyl radicals. The formation of benzyl radicals in the reaction between hydroxyl radicals and phenylacetic acid would appear to be an analogous case.³⁶ Decarboxylation has also been found³⁷ to occur when mandelic acid is δ -irradiated. In the reaction between *N*-iodosuccinimide and trifluoroacetic acid, trifluoromethyl iodide and succinimide are formed.³⁸ It is believed that a protonated succinimide radical is responsible for the hydrogen abstraction.

There are several examples which illustrate that C-H bonds adjacent to carboxyl or ester groups are deactivated towards acceptor radical attack. For example, hydrogen is abstracted preferentially from the β -position of propionic acid by hydroxyl radicals;³⁵ the chlorination of cyclobutanecarboxylic acid produces only 2- and 3-chloro-compounds;³⁹ ethoxyl radicals abstract hydrogen from the benzylic position in β -phenylpropionic acid;⁴⁰ and methoxyl radicals react at the benzylic position in benzyl dimethylmalonate.⁴⁰ The deactivating effect decreases as the electron affinity of the radical decreases. Methyl radicals, for instance, abstract hydrogen from C-H bonds adjacent to the ester groups of

³² J. McDonald Blair, D. Bryce-Smith, and B. W. Pengilly, *J. Chem. Soc.*, 1959, 3174.

³³ D. H. Hey, S. Orman, and G. H. Williams, *J. Chem. Soc.*, 1965, 101 and previous papers cited.

³⁴ J. K. Hambling, D. H. Hey, and G. H. Williams, *J. Chem. Soc.*, 1962, 487.

³⁵ W. T. Dixon, R. O. C. Norman, and A. L. Buley, *J. Chem. Soc.*, 1964, 3625.

³⁶ H. Fischer, *Z. Naturforsch.*, 1965, 20a, 488.

³⁷ S. A. Barker, J. S. Brimacombe, and D. J. Milner, *J. Chem. Soc. (C)*, 1966, 511.

³⁸ D. D. Tanner, *J. Amer. Chem. Soc.*, 1964, 86, 4674.

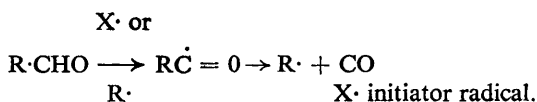
³⁹ W. A. Nevill, D. S. Frank, and R. D. Trepka, *J. Org. Chem.*, 1962, 27, 422.

⁴⁰ H. C. McBay, O. Tucker, and A. Milligan, *J. Org. Chem.*, 1954, 19, 1003.

benzyl dimethylmalonate.⁴⁰ In the reaction between the t-butoxyl radicals and propionic acid, attack on the α -C-H bonds was sixteen times more rapid than that on the β -C-H bonds.⁴¹ This suggests that the t-butoxyl radical has a relatively low electron affinity.

Hey and his co-workers found⁴² that the alkylation of diethyl malonate and related compounds can be brought about by the peroxide-initiated addition of the parent esters to olefins.

Aldehydes.—The radical-initiated decarbonylation of aliphatic aldehydes has been extensively studied. The t-butoxyl radical is particularly effective as a chain initiator:



The alkyl radical, produced by decarbonylation of the intermediate acyl radical, continues the chain reaction by abstracting hydrogen from an aldehyde group. Stable radicals (*e.g.*, $\text{Me}_2\dot{\text{C}}\text{-CO}_2\text{Me}$) are less efficient as initiators since an initiator and an acyl radical combine, so terminating the chain.⁴³ The amount of decarbonylation in such reactions has been found⁴⁴ to be significantly increased by the addition of a thiol which acts as a hydrogen carrier, *i.e.*, a thiyl radical abstracts hydrogen from an aldehyde group efficiently, and a hydrogen from the thiol group so formed is easily abstracted⁴⁵ by an alkyl radical.

The generation of acyl radicals from aldehydes by means of free radicals has found application in the study of the stabilities of cyclopropyl,⁴⁶ bridgehead⁴⁷ and other cyclic radicals,⁴⁸ radical rearrangements,⁴⁹ and intramolecular acylations.⁵⁰ The peroxide-initiated reaction of aldehydes with carbon tetrachloride⁵¹ or sulphuryl chloride⁵² produces acyl halides.

The acyl radicals, obtained by hydrogen abstraction from aromatic⁵³ and conjugated unsaturated aldehydes, are relatively stable and do not normally decarbonylate.

Difluoramino-⁵⁴ and diphenylphosphino-radicals⁵⁵ have been found to

⁴¹ A. L. J. Beckwith, *Austral. J. Chem.*, 1960, **13**, 244.

⁴² J. C. Allen, J. I. G. Cadogan, B. W. Harris, and D. H. Hey, *J. Chem. Soc.*, 1962, 4468.

⁴³ E. F. R. Harris and W. A. Waters, *J. Chem. Soc.*, 1952, 3108.

⁴⁴ K. E. J. Barnett and W. A. Waters, *Discuss. Faraday Soc.*, 1953, **14**, 221.

⁴⁵ L. H. Slaugh, *J. Amer. Chem. Soc.*, 1959, **81**, 2262.

⁴⁶ D. I. Schuster and J. D. Roberts, *J. Org. Chem.*, 1962, **27**, 51.

⁴⁷ D. E. Applequist and L. Kaplan, *J. Amer. Chem. Soc.*, 1965, **87**, 2194.

⁴⁸ J. W. Wilt and A. A. Levin, *J. Org. Chem.*, 1962, **27**, 2319.

⁴⁹ R. Kh. Freidlina, *Adv. Free Radical Chem.*, 1965, **1**, 211.

⁵⁰ W. H. Urry, D. J. Trecker, and H. D. Hartzler, *J. Org. Chem.*, 1964, **29**, 1663; R. Dolon, Y. Chretien-Bessiere, and H. Desalbres, *Compt. rend.*, 1964, **258**, 603.

⁵¹ S. Winstein and F. H. Seubold, *J. Amer. Chem. Soc.*, 1947, **69**, 2916.

⁵² M. Arai, *Bull. Chem. Soc. Japan*, 1965, **38**, 252.

⁵³ F. R. Rust, F. H. Seubold, and W. E. Vaughan, *J. Amer. Chem. Soc.*, 1948, **70**, 3258.

⁵⁴ R. C. Petry and J. P. Freeman, *J. Amer. Chem. Soc.*, 1961, **83**, 3912.

⁵⁵ R. S. Davidson, R. A. Sheldon, and S. Trippett, unpublished results.

abstract hydrogen from the aldehyde group. Amides were obtained as products from the reaction with the nitrogen radical whereas the phosphorus radical gave products derived by the addition of diphenylphosphine to the aldehyde.

Ethers.—C-H bonds adjacent to the oxygen atom in ethers are particularly reactive towards free radicals and this is due to the ability of the oxygen atom to stabilise polar contributions to the transition state and also the incipient radicals. C-H bonds flanked by two oxygen atoms show an enhanced reactivity.⁵⁶

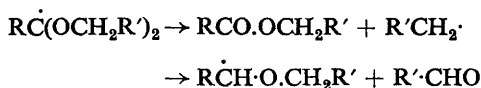
The reactions of ethers with methyl,⁵⁶ phenyl,² alkoxy,⁵⁷ peroxy-¹¹ acyloxy-⁵⁸ and halogen radicals⁵⁹ have been investigated. The decomposition of acyl peroxides in ethers is particularly rapid. Apparently the intermediate α -alkoxyalkyl radicals attack the peroxide which brings about induced decomposition.

The abstraction of hydrogen from cyclic ethers has received attention.⁵⁷ Usually, if the intermediate α -alkoxyalkyl radical cannot combine with another radical to form a stable product, ring-opening occurs with the formation of a carbonyl compound:



In the reaction between *t*-butyl hypochlorite and substituted ethylene oxides, ring-opening and the formation of chloroethylene oxides were found¹⁹ to be in competition.

Abstraction of hydrogen from acetals by the *t*-butoxyl radical was found⁶⁰ to produce both esters and aldehydes:



In an analogous reaction with 2-methoxytetrahydrofuran, esters were formed.⁶¹

In the reaction between bromine radicals and benzyl ethers, alkylated benzaldehyde bromohydrins were formed,⁶² which readily decomposed to benzaldehyde and alkyl bromide. In the reactions of nuclear-substituted benzyl ethers with bromine⁶³ and peroxy-radicals,¹¹ the substituents had little effect upon the reaction.

⁵⁶ C. L. Aldridge, Z. B. Zachry, and E. A. Hunter, *J. Org. Chem.*, 1962, 27, 47.

⁵⁷ T. J. Wallace and R. J. Gritter, *J. Org. Chem.*, 1962, 27, 3067.

⁵⁸ W. E. Cass, *J. Amer. Chem. Soc.*, 1947, 69, 500.

⁵⁹ H. Böhme and A. Dörries, *Chem. Ber.*, 1956, 89, 723.

⁶⁰ L. P. Kuhn and C. Wellman, *J. Org. Chem.*, 1957, 22, 774.

⁶¹ E. S. Huyser, *J. Org. Chem.*, 1960, 25, 1820.

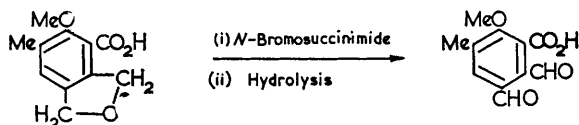
⁶² R. L. Huang and H. K. Lee, *J. Chem. Soc.*, 1964, 5957, 5963.

⁶³ R. E. Lovins, L. J. Andrews, and R. M. Kelfer, *J. Org. Chem.*, 1965, 30, 1577.

The oxidation of benzaldehyde acetals by *N*-bromosuccinimide has been found⁶⁴ to produce alkyl benzoates and alkyl bromides.

t-Butoxyl radicals have been used⁶⁵ to abstract hydrogen from benzaldehyde cyclic acetals. The intermediate radical decomposes to give an ester. If the ether ring contains substituents, a mixture of isomeric esters is obtained. The reactions of a number of nuclear-substituted dibenzyl ethers with *t*-butoxyl and bromine radicals have been reported.⁶⁶ The observation that a larger polar effect operates in the reaction with the more reactive *t*-butoxyl radical than with the less reactive bromine radical is rather surprising.

The oxidation of substituted dihydroisobenzofurans by *N*-bromosuccinimide has been found⁶⁷ to produce substituted *o*-benzodialdehydes.



Alkylphenols and Alkylthiophenols.—In reactions between these compounds and free radicals, substitution competes with hydrogen abstraction. There is evidence⁶⁸ that *t*-butoxyl radicals abstract hydrogen from anisole with the formation of phenoxy-methyl radicals which under thermal conditions (140°) undergo substitution reactions and under photolytic reactions dimerise. The reaction between *t*-butoxyl radicals and methyl phenyl sulphide produced⁶⁹ thiophenoxy-methyl radicals which dimerised under thermal conditions (140°) and were demethylated under photolytic conditions.

Alcohols, Phenols, and Oximes.—A wide variety of radicals, *e.g.*, alkyl,⁷⁰ alkoxy,⁷¹ hydroxyl,⁷² nitrogen,⁷³ and sulphur⁷⁴ radicals, abstract hydrogen from alcohols. In general, the α -C-H bond (*D*, 90 kcal./mole) and not the O-H bond (*D*, 108 kcal./mole) is attacked. This was demonstrated by Kharasch, Rowe, and Urry⁷⁰ who studied the reaction between diacetyl peroxide and alcohols containing α -C-D bonds. In all cases a high yield of deuteriomethane (CH₃D) was obtained. The inertness of the O-H bond was shown by studying the analogous reaction with deuterio-*t*-butyl alcohol [(CH₃)₃COD] in which deuteriomethane was not produced. E.s.r. spectroscopic evidence has since been

⁶⁴ S. O. Lawesson and T. Busch, *Arkiv Kemi*, 1961, 17, 421.

⁶⁵ E. S. Huyser and Z. Garcia, *J. Org. Chem.*, 1962, 27, 2716.

⁶⁶ R. L. Huang, H. H. Lee, and S. H. Ong, *J. Chem. Soc.*, 1962, 3336; R. L. Huang, H. H. Lee, and M. S. Malhotra, *ibid.*, 1964, 5947.

⁶⁷ J. Blair, W. R. Logan, and G. T. Newbold, *J. Chem. Soc.*, 1956, 2443.

⁶⁸ H. B. Henbest, J. A. W. Reid, and C. J. M. Stirling, *J. Chem. Soc.*, 1961, 5239.

⁶⁹ H. B. Henbest, J. A. W. Reid, and C. J. M. Stirling, *J. Chem. Soc.*, 1964, 1220.

⁷⁰ M. S. Kharasch, J. L. Rowe, and W. H. Urry, *J. Org. Chem.*, 1951, 16, 905.

⁷¹ D. C. Neckers, A. P. Schaap, and J. Hardy, *J. Amer. Chem. Soc.*, 1966, 88, 1265.

⁷² L. J. Leyshon and D. H. Volman, *J. Amer. Chem. Soc.*, 1965, 87, 5565.

⁷³ A. Schönberg and A. Mustafa, *J. Amer. Chem. Soc.*, 1951, 73, 2401; B. R. Cowley and W. A. Waters, *J. Chem. Soc.*, 1961, 1228.

⁷⁴ M. Nakasaki, *J. Chem. Soc. Japan*, 1953, 74, 405.

obtained⁷⁵ which suggested that attack occurs at the α -C-H bonds. It was found⁷⁶ that acyl peroxides undergo induced decomposition in alcohols (cf. the reaction with ethers). A few cases have been reported of abstraction from the hydroxyl group. The $\text{Me}_2\text{C} = \dot{\text{C}}\text{H}$ radical abstracts⁷⁷ deuterium from deuterioethanol (EtOD). It has also been found⁷⁸ that some cyclopropanols on oxidation give products consistent with the formation of alkoxy radicals. Recently it has been suggested⁷⁹ that diphenylphosphino-radicals abstract the hydroxylic hydrogen by way of an initial attack upon the oxygen atom.

The formation of aryloxy-radicals from phenols has recently been reviewed.⁸⁰ Some of the reagents which bring about these oxidations have been found⁸¹ to oxidise oximes, with the formation of iminoxyl radicals.

N-H, P-H, and S-H Bonds.—These bonds have been shown to be particularly reactive towards free radicals. This undoubtedly reflects the ability of the hetero-atom to stabilise polar structures which contribute to the transition state.

The N-H bond. Alkyl,⁸² peroxy,⁸³ and stable⁸⁴ free radicals have been found to abstract hydrogen. The N-H bond in diphenylamine is 3.3 times more reactive towards phenyl radicals than the benzylic C-H bonds in diphenylmethane. In some abstraction it is possible that radical ions are intermediates, *e.g.*, in the reaction between primary aromatic amines and diphenylpicrylhydrazyl radicals.⁸⁴

The P-H bond. The free radical-initiated reaction in which a primary or secondary phosphine is added to an olefin has been reviewed.⁸⁵ Peroxides, acyl peroxides, and azonitriles act as initiators. The P-H bond in diphenylphosphine is thirty times more reactive towards phenyl radicals than diphenylamine. The stable diphenylamino-radical can abstract hydrogen⁸⁶ from P-H bonds.

The S-H bond. Abstraction of hydrogen from S-H bonds has received particular attention⁸⁷ since it is the first step in the addition of thiols to olefins. Peroxides and azo-compounds are efficient initiators. The reactivity of S-H bonds towards alkyl radicals has been commented upon⁴⁴ (p. 255). Difluoramino-,⁸⁸ diphenylamino-,⁸⁹ and triphenylmethyl radicals⁹⁰ abstract hydrogen from thiols.

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