MECHANISMS FOR CARBON-HYDROGEN BOND BREAKAGE

By E. S. LEWIS, B.S., M.A., PH.D.
(DEPARTMENT OF CHEMISTRY, THE RICE INSTITUTE, HOUSTON, TEXAS)

and M. C. R. SYMONS, PH.D.
(DEPARTMENT OF CHEMISTRY, THE UNIVERSITY, SOUTHAMPTON)

THE purpose of this Review is to present a variety of reactions involving the breaking of C–H bonds in terms of the available mechanisms, with stress upon their interrelation and the reasons for the predominance of certain mechanisms. We do not aim to cover all the recent examples of reactions in which C–H bonds are broken ; instead, we select pertinent examples. The comprehensive scheme below is intended for classification rather than absolute representation of mechanism.

A. Unassisted breakage.
B. Assisted breakage.
  1. Attack by nucleophilic reagents on carbon.
  2. Attack by nucleophilic reagents on hydrogen.
  3. Attack by radical reagents on carbon.
  4. Attack by radical reagents on hydrogen.
  5. Attack by electrophilic reagents on carbon.
  6. Attack by electrophilic reagents on hydrogen.
  7. Unimolecular reactions with intramolecular assistance.

Any classification of this sort is inevitably somewhat arbitrary, and it is possible to list many reactions under more than one heading. This difficulty arises in part because reactions in solution are often co-operative in nature. Thus the pairs of reactions considered in sections B1 and B6, B2 and B5, B3 and B4, are complementary and it is often merely preference which stage in the reaction is used for the classification. We focus attention on that part of a reaction sequence in which the C–H bond is broken, although this stage in an over-all reaction is not necessarily the slowest or most significant, with the belief that this approach will prove fruitful.

A. Unassisted breakage

Unassisted heterolysis does not seem to occur (see sections B1 and B5). Unassisted homolysis of C–H bonds, by heat or on ultraviolet irradiation, is very rare, since organic molecules usually contain weaker bonds which are broken preferentially.

Probable examples of direct photochemical cleavage are :

$CH_2O \xrightarrow{h\nu} HCO\cdot + H\cdot$ . . . (1) [1]

and $CH_3\cdot CH{=}CH_2 \xrightarrow{h\nu} \cdot CH_2\cdot CH{=}CH_2 + H\cdot$ . . (2) [2]

and an example of pyrolysis is :

$CH_3\cdot CH_2\cdot \xrightarrow{500^\circ} CH_2{=}CH_2 + H\cdot$ . . . (3) [3]

Reaction (3) is favoured by the formation of a new bond and by the fact that the starting material is itself a highly reactive radical.

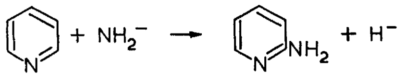
However, this is not a characteristic behaviour of ethyl radicals in the liquid phase below 100°,[4] and there is good evidence that the reverse occurs readily at room temperature.[5] The conclusion that reaction (3), which is extremely favoured compared with, say, (1) or (2), occurs only at high temperature (*e.g.*, 500°) will be important in later discussion (section B3).

B. Assisted breakage

B1. Attack by Nucleophilic Reagents on Carbon.—

$$B:^- + C\text{–}H \longrightarrow B\text{–}C + H^-$$

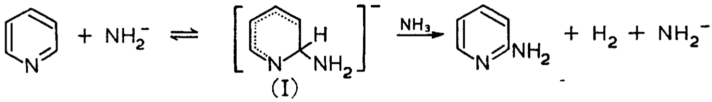
Since the hydride ion is an extremely powerful base, its conjugate acid being the hydrogen molecule, this reaction as written would appear improbable in the absence of a reagent able to react with the hydride ion, and no authentic examples of its occurrence have been found. However, as soon as one allows under this heading reactions in which H^- never appears as such, many proposed mechanisms including this step can be quoted, nearly all involving displacement of H^- from aromatic nuclei. This specificity may be understood if it is postulated that an intermediate must be formed, having a life long enough to give it a reasonable chance of colliding favourably with that reagent which reacts with the " hydride ion ". For example, the reaction :



........(4)

$$H^- + NH_3 \longrightarrow H_2 + NH_2^-$$

could be written in the form :



............(5)

---

[1] Steacie, " Atomic and Free Radical Reactions ", Reinhold, New York, 2nd edn., 1954, p. 275.

[2] Lossing, Marsden, and Farmer, *Canad. J. Chem.*, 1956, **34,** 701.

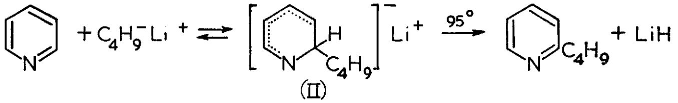
[3] Rice and Herzfeld, *J. Amer. Chem. Soc.*, 1934, **56,** 284.

[4] Smidt, Rembaum, and Szwarc, *ibid.*, 1956, **78,** 3315.

[5] Melville and Robb, *Proc. Roy. Soc.*, 1949, *A*, **196,** 494 ; Bradley, Melville, and Robb, *ibid.*, 1956, *A*, **236,** 454, 446.

If formulation (5) is accepted, the net reaction is clearly a result of co-operation between the nucleophilic amide ion and the ammonia molecule acting as an electrophile. Indeed, provided that the life of intermediate (I) is sufficiently long, then the actual C–H bond-breaking process is strictly the result of an electrophilic attack on hydrogen. [A possible alternative route for the conversion of complex (I) into the products involves a cyclic intermediate and is properly considered under section B7.]

A reaction which comes close to the extreme of actual displacement of H^- is that described by Ziegler and Zeiser.[6] An adduct is readily isolated,



............(6)

and when the mixture is heated lithium hydride is precipitated. Although the structure of this adduct is not established, it seems reasonable to formulate it as (II); the C–H bond-breaking process may then be represented as resulting from an electrophilic attack on H by Li^+. (Covalent bonding in the LiH molecule should be considerable, although the crystalline solid is essentially ionic.)

Although S_N2 displacement of H^- in saturated aliphatic systems is not found, there are systems analogous to those discussed above in which certain intermediates exhibit a strong tendency to donate H^-. Thus, just as the intermediates (I) or (II) are powerful H^- donors, so also are the following ions, which tend to lose H^-, according to the equations:

$$\begin{aligned} CH_3{\cdot}CH_2^- &\rightarrow CH_2{=}CH_2 + H^- \\ R_2CHO^- &\rightarrow R_2C{=}O + H^- \\ R{\cdot}CHO_2^{2-} &\rightarrow R{\cdot}CO_2^- + H^- \end{aligned}$$

It is unlikely that *free* hydride ion, H^-, is lost from any of these intermediates, and their reactions are properly considered under section B6. For example, Grignard reagents containing hydrogen may effect reduction rather than alkylation,[7] and the Cannizzaro reaction probably proceeds by transfer of H^- from $R{\cdot}CHO_2^{2-}$.[8]

That alkoxide ions are reducing agents is well known. Since alkali hydrides dissolve unchanged in molten alkali, it might be thought that the dissolution of an alcohol in molten alkali would result in loss of H^-, which would then be unable to react with the medium. However, the resulting aldehyde or ketone would readily lose a proton, and the resulting water molecule or another aldehyde or ketone molecule could be pictured as reacting with H^- to give hydrogen. In fact, if ethanol vapour is passed through molten alkali at 250—300° hydrogen is evolved, although acetaldehyde, which is almost certainly the initial product, is further decomposed.[9]

---

[6] Ziegler and Zeiser, *Ber.*, 1930, **63**, 1847.

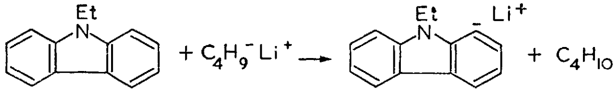
[7] Whitmore, Whitaker, Mosher, Breivik, Wheeler, Miner, Sutherland, Wagner, Clapper, Lewis, Luse, and Popkin, *J. Amer. Chem. Soc.*, 1941, **63**, 643.

[8] Hammett, "Physical Organic Chemistry", McGraw-Hill Co., New York, 1940, p. 351.

[9] Fry and Schulze, *J. Amer. Chem. Soc.*, 1926, **48**, 958.

Once again, however, it is not necessary to formulate the reaction in such a way as to involve free hydride ion, an alternative representation being the direct extrusion of molecular hydrogen from the ethoxide ion, a mechanism which should be considered under section B7.

An interesting example of competition between nucleophilic attack on carbon and on hydrogen is to be found by comparing the reaction between *n*-butyl-lithium and pyridine, resulting in alkylation (reaction 3), and 9-ethylcarbazole, resulting in metallation (reaction 7).



(7)

This difference in reactivity is caused mainly by the far greater susceptibility of the pyridine ring to nucleophilic attack.

B2. Attack by Nucleophilic Reagents on Hydrogen.—Nucleophilic attack on hydrogen bonded to carbon is the most common C–H bond-breakage in organic chemical practice. Nucleophilic attack on hydrogen is an acid–base reaction in Brönsted's sense, but most of the reactions of hydrogen bonded to carbon differ from those of familiar acids in that they are perceptibly slow and have activation energy. A substance with a hydrogen atom on carbon susceptible to nucleophilic attack is then an example of a " pseudo-acid " [10] or a secondary acid.[11]

Reaction (8) of an ordinary hydrocarbon requires an exceedingly strong base. With saturated hydrocarbons equilibria of the form (8) can be detected

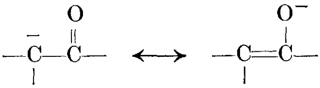
$$R_3CH + B^- \rightleftarrows R_3C^- + HB \quad . \quad . \quad . \quad (8)$$

with an organosodium compound as the base B^-, but values of the equilibrium constants are not known. Observations on the extent of the metallation with pentylsodium [12] show that the ease of ionisation of the benzyl-hydrogen atom falls in the order $Ph{\cdot}CH_3 > Ph{\cdot}CH_2R > Ph{\cdot}CH(CH_3)_2$, that is, in the order expected from the inductive effect of the alkyl group. Thus the formation of carbanions is affected in the opposite way to the formation of carbonium ions by alkyl groups. It is not known whether experiments of this sort are subject to equilibrium or to kinetic control. With hydrogen attached to an unsaturated carbon atom, the order of decreasing ease of ionisation is $C{\equiv}C{-}H > C{=}C{-}H > {-}C{-}H$. This effect of the change in the hybridisation of the bond on the acidity has been discussed by Mullikan.[13] Doubtless the reactions of terminal acetylenes under basic conditions often have ionisation as the initial step, and the familiar preparation of acetylenic Grignard reagents by reaction of acetylenes with saturated Grignard reagents is also a reaction of this type. Proton-transfer from the sp^2-hybridised carbon atom is illustrated by the metallation of aromatic compounds and olefins with alkyl-lithium, a reaction of

[10] Hantzsch and Schultze, *Ber.*, 1896, **29,** 2251.
[11] Lewis and Seaborg, *J. Amer. Chem. Soc.*, 1939, **61,** 1886.
[12] Morton, Little, and Strong, *ibid.*, 1943, **65,** 1339.
[13] Mullikan, *J. Chem. Phys.*, 1935, **3,** 573.

important preparative value.[14] Complications of this simple proton-transfer by participation of the metal ion in various ways must be considered with even a crude refinement of the mechanism. An interesting example of proton-transfer from aromatic systems occurs also with more conventional bases as the first step in the benzyne mechanism[15] of nucleophilic displacement in aromatic systems.

More important than the reactions producing alkyl or aryl anions are the reactions producing carbanions stabilised by resonance. The familiar enolate ions result from the ionisation of hydrogen adjacent to a carbonyl group and are typical examples of triad resonance-stabilised anions. Because of this resonance and an inductive effect a ketone has an acid disso-



$$-\overset{-}{\underset{|}{C}}-\overset{\overset{O}{\|}}{C}- \longleftrightarrow -\underset{|}{C}=\overset{\overset{O^-}{|}}{C}-$$

ciation constant more than 10^{20} times that estimated for methane, and a second carbonyl group on the same carbon produces a further increase in acidity such that it is measurably ionised in water ; the ketonic form of acetylacetone is reported[16] to have $pK_a = 8{\cdot}9$. Analogous carbanions result from ionisation of the α-hydrogen atoms in esters, aldehydes, anhydrides, nitriles, and nitro-paraffins. An interesting hydrocarbon example of a resonance-stabilised anion is the symmetrical and aromatic anion which results from the attack of a base on *cyclo*pentadiene. Since all of these carbanions can react with carbonyl groups, with alkyl halides, and with conjugated carbonyl compounds, the number of possible reactions of synthetic value is very large, and changes in the nature of the attacking base add further variety to these carbanion reactions.

Ionisation of a C–H bond may be readily detected by pH measurements if a substantial concentration of carbanion is formed. More commonly, the carbanion is present in minute concentration and is detected only by its reactions. Thus the isolation of a product of one of the base-catalysed reactions of the previous paragraph can now be taken as evidence of the presence of a carbanion in the reaction mixture. More sensitive tests involve the far more rapid reaction of the carbanions with halogen, and the rate of ionisation of a ketone by base can be measured by the rate of bromination. Other rapid reactions of carbanions are racemisation followed by protonation, and direct reaction with a hydrogen isotope, resulting in over-all base-catalysed exchange of hydrogen with solvent deuterium of the parent compound.[17]

Nucleophilic attack on hydrogen is also promoted by inductive effects. A clear example is the reaction of chloroform with aqueous sodium hydroxide. The initial step of both hydrolysis and deuterium exchange is proton-

---

[14] Gilman and Morton, in *Organic Reactions,* Vol. VIII, pp. 258.

[15] Roberts, Semenow, Simmons, and Carlsmith, *J. Amer. Chem. Soc.,* 1956, **78,** 601 ; Wittig, *Naturwiss.,* 1942, **30,** 696.

[16] Schwartzenbach and Felder, *Helv. Chim. Acta,* 1944, **27,** 1701.

[17] Ref. 8, p. 97.

transfer (9) assisted by the combined inductive effect of the three halogen atoms.[18] A similar case of electrostatic facilitation of ionisation resulting

$$Cl_3CH + \dot{O}H^- \longrightarrow Cl_3C^- + H_2O \quad . \quad . \quad . \quad (9)$$

from only one halogen is found in the "alpha-elimination" detected in the reaction of 1-bromo-octane with sodamide,[19] where the initial step is the attack of amide ion on the primary hydrogen. Inductive facilitation of proton loss is also shown in studies of the deuterium exchange of 'onium salts, although resonance-stabilisation of the "ylids" by contribution of structures using *d*-orbitals apparently provides more important help when it is possible.[20]

An alternative way to avoid an unfavourable carbanion is to lose a fairly stable anion at the same time as a proton, leaving a neutral molecule. The large class of second-order eliminations (*E*2) may be so described. The normal mode of attack of a base on the hydrogen atom of an alkyl halide does not produce an intermediate carbanion;[21] instead, halide ion is lost from the 1-position as the base removes a proton at the 2-position, and an olefin is formed in one step. The transition state has important olefinic character, as shown by the formation of the most stable olefin, according to the Saytzeff rule. The stereochemical requirements are rather rigorous, with the attacking base and the leaving halogen on opposite sides of the plane of the incipient olefin.[22] When this configuration is unattainable for steric reasons, the elimination is conspicuously slower and, in at least one case, the carbanion is an intermediate.[23] Analogous eliminations to give carbon–nitrogen triple bonds from *N*-chloroimides [24] and carbon–oxygen double bonds from alkyl peroxides,[25] nitrites,[26] and chromates [27] by attack of bases have been studied and are mechanistically almost identical with the olefin-forming *E*2 reaction.

In all these cases of nucleophilic attack on hydrogen an essentially linear configuration about the hydrogen in the transition state can be assumed, both by analogy with the stereochemically indicated linear transition state for nucleophilic attack on carbon, and by analogy with the hydrogen bond, where it has been shown that the hydrogen is most favourably located between two electronegative atoms on the line connecting them. Further support is given by the substantial decrease in rate on substitution of deuterium for the hydrogen in question. Since this isotope effect is frequently large enough to require almost complete loss of the C–H stretching vibration in the transition state, a linear transition state is indicated. The absence of a large isotope effect does not require a non-linear transition

---

[18] Hine, *J. Amer. Chem. Soc.*, 1950, **72**, 2438.

[19] Hill, Judge, Skell, Kantor, and Hauser, *ibid.*, 1952, **74**, 5599.

[20] Doering and Hoffmann, *ibid.*, 1955, **77**, 521.

[21] Skell and Hauser, *ibid.*, 1945, **67**, 1661.

[22] Barton, *J.*, 1953, 1027.

[23] Cristol and Fox, *J. Amer. Chem. Soc.*, 1953, **75**, 2647.

[24] Hauser, LeMaistre, and Runsford, *ibid.*, 1935, **57**, 880.

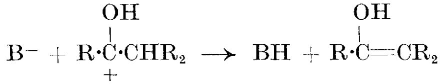
[25] Kornblum and de la Mare, *ibid.*, 1951, **73**, 880.

[26] Baker and Easty, *J.*, 1952, 1208.

[27] Holloway, Cohen, and Westheimer, *J. Amer. Chem. Soc.*, 1951, **73**, 65.

state, however, and a review of hydrogen-isotope effects [28] lists many examples of smaller but still significant effects in proton-transfers.

The transfer of protons from an electron-deficient molecule is susceptible to the same influences as is the transfer from saturated systems, but some unique features warrant a separate discussion. Acid-catalysed enolisation of ketones is closely analogous to the situations already discussed and can be represented as a nucleophilic attack on the conjugate acid of the ketone (10), where the contributing structure shown for the conjugate acid emphasises the electron-deficiency. This reaction is very likely the slow step in the enolisation catalysed by the general acid HB.[29] An alternative termolecular one-step mechanism has been extensively discussed,[30] but the distinction is not especially pertinent in this discussion. It is clear that reaction (10) will be much faster than the corresponding proton-transfer to the same base B^- from the neutral ketone, because of the inductive effect of the positive charge in the conjugate acid. Thus, carbonyl-condensation reactions analogous to the base-catalysed ones occur with acid-catalysis, and reaction (10) is an important step.



$$B^- + R{\cdot}\underset{+}{\overset{\overset{\displaystyle OH}{|}}{C}}{\cdot}CHR_2 \longrightarrow BH + R{\cdot}\overset{\overset{\displaystyle OH}{|}}{C}{=}CR_2 \quad . \quad . \quad (10)$$

Olefin-forming proton-loss from less stable carbonium ions is a very important fate of these highly reactive molecules. It is the fast second step in the *E*1 elimination.[31] The observation that the same mixture of olefins and substitution products is obtained on solvolysis of the different *tert*.-amyl halides [32] shows not only that the same intermediate occurs in the substitution and the elimination process, which is halogen-free, but also that the rate of the elimination step is independent of the anion. This probably shows that the solvent is the base in reaction (11), although equal reactivity is an alternative possibility. In contrast to the cases discussed above, substitution of deuterium for hydrogen has only a very small effect on the rate.[33]

$$B + R_2C^+{\cdot}CHR'_2 \longrightarrow R_2C{=}CR'_2 + BH^+ \quad . \quad . \quad (11)$$

Rationalisations of this effect have been offered,[34, 35] but still another factor must be considered. In the reverse reaction, the hydration of olefins, Taft has been forced to conclude that the rate-determining step was the isomerisation of the olefin–proton π-complex to the conventional carbonium ion.[36] In accordance with the principle of microscopic reversibility, the carbonium ion, on the way to the olefin, must first pass through the π-com-

---

[28] Wiberg, *Chem. Rev.*, 1955, **55**, 713.

[29] Dawson and Spivey, *J.*, 1930, 2180.

[30] Lowry, *J.*, 1927, 2554 ; Bell, *J.*, 1953, 88 ; Swain, *J. Amer. Chem. Soc.*, 1950, **72**, 4578.

[31] Hughes, *ibid.*, 1935, **57**, 708.

[32] Ingold, " Structure and Mechanism in Organic Chemistry ", Cornell Univ. Press, Ithaca, 1952, p. 426.

[33] Shiner, *J. Amer. Chem. Soc.*, 1953, **75**, 2925.

[34] Boozer and Lewis, *ibid.*, 1954, **76**, 794.

[35] Hammond, *ibid.*, 1955, **77**, 334.

[36] Taft, *ibid.*, 1952, **74**, 5372.

plex, and there is no reason to expect a very large isotope effect for this process.

It is seldom possible to detect the base in reaction (11), although it is clearly necessary to avoid the energetic problems of creating a free proton. In at least one case, the need for a base to accomplish the elimination is experimentally demonstrable. In the commercial alkylation of *iso*butane with butanes in the presence of sulphuric acid, the undesirable elimination (11) from the eight-carbon cation competes with the hydride-ion transfer (12).

$$R_2C^+\cdot CHR'_2 + (CH_3)_3CH \longrightarrow R_2CH\cdot CHR'_2 + (CH_3)_3C^+ \quad . \quad (12)$$

At low acidities and hence high bisulphate ion concentration, polymeric products derived from the olefin of reaction (11) predominate, but at high acidities the saturated product of reaction (12) is produced. Since the hydride-transfer does not involve acid, the change in relative rates must be due to retardation of the elimination process (11) by reduction in concentration of the base B (HSO_4^-).

A special case of elimination from carbonium ions is the second step of aromatic substitution discussed more extensively elsewhere in this Review. In only a few cases is the necessity for a base obvious in this reaction. In sulphonation there is a significantly slower replacement of tritium than of hydrogen,[37] and in some diazo-coupling reactions a large isotope effect and general basic-catalysis have both been observed.[38]

B3. Attack by Radical Reagents on Carbon.—

$$R\cdot + C{-}H \longrightarrow R{-}C + H\cdot$$

Displacement of a hydrogen atom by a radical other than another hydrogen atom is energetically most unfavourable. However, although it is not nowadays postulated as a significant process in radical reactions involving aliphatic compounds, it is often included as a separate stage in aromatic radical substitution. Thus, in two recent reviews [39, 40] on aromatic substitution by aryl radicals such displacements are continually depicted. Although the alternative outlined below is considered,[40] the conclusion finally reached is that " predominance of the reaction

$$C_6H_5X + C_6H_5\cdot \longrightarrow C_6H_5\cdot C_6H_4X + H\cdot \quad . \quad . \quad . \quad (13)$$

is shown to be substantiated ".

Apart from being energetically unfavourable, there is a variety of reasons why such a displacement is unlikely. The evidence marshalled in favour of this displacement [40] is significant as evidence *against* initial radical attack on hydrogen but in no sense justifies the concept of hydrogen-atom displacement.

One argument against the concept of hydrogen-atom displacement is that, during phenylation with benzoyl peroxide in the absence of added oxidising agents, benzoic acid is formed in high yield. The free hydrogen

---

[37] Melander, *Arkiv Kemi*, 1950, **2**, 213.

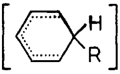
[38] Zollinger, *Helv. Chim. Acta*, 1955, **38**, 1623 ; *Experientia*, 1956, **12**, 165.

[39] Dermer and Edminson, *Chem. Rev.*, 1957, **57**, 77.

[40] Augood and Williams, *ibid.*, p. 123.

atom is far too reactive to show such selectivity, and the $Ph{\cdot}CO_2{\cdot}$ radical must surely have abstracted hydrogen from some intermediate to give benzoic acid.

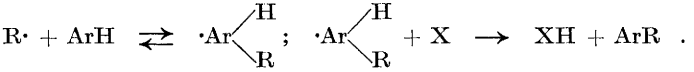
Other factors are best considered in terms of the intermediate radical (III). There is every reason to believe that such an intermediate would have fair stability, and that the rate-determining stage in aromatic radical substitution is the step leading to the formation of this radical.[41] In particular, the absence of any isotope effect in the reaction between tritiobenzene and benzoyl peroxide[42] shows that C–H bond breaking is not appreciable in the transition state.



(III)

If the intermediate formation of a radical-addition complex of this sort is accepted, there is no need to postulate direct loss of a hydrogen atom to explain the observed results, and, indeed, such a step appears most improbable although the intermediate could be described as a highly efficient hydrogen-atom donor. In section A, reference was made to the high-temperature decomposition of ethyl radicals into ethylene and hydrogen atoms, but it was stressed that such decomposition is not detected at room temperature. Loss of hydrogen by ethyl would be more favourable energetically than loss of hydrogen by an intermediate of type (III) and it can accordingly be concluded that hydrogen is lost only as a consequence of attack by another molecule or radical.

We therefore formulate the process of radical attack on aromatic systems leading to substitution in the ring as :



$$R{\cdot} + ArH \rightleftarrows {\cdot}Ar\begin{matrix} H \\ R \end{matrix} \; ; \quad {\cdot}Ar\begin{matrix} H \\ R \end{matrix} + X \longrightarrow XH + ArR \quad . \qquad (14)$$

where X may be another radical, such as $Ph{\cdot}CO_2{\cdot}$, or a reactive molecule such as quinone.

In some cases addition occurs preferentially, as, for example, in many reactions of anthracene[43] and in photochlorination of benzene. Radical attack on ring-hydrogen atoms does not seem to be a common step, presumably because the resulting phenyl-type radical is not stabilised by resonance, in contrast to radicals formed by addition.

Further evidence for this contention comes from the observation that hydrogen-atom displacement seems not to be observed in saturated systems, even with reactive radicals in the gas phase. One can trace an interesting parallel in the understanding of mechanism by recalling that in 1931 Pease and Walz[44] studied the chlorination of methane and proposed the following chain process :

$$\left.\begin{aligned} Cl{\cdot} + CH_4 &\longrightarrow CH_3Cl + H{\cdot} \\ H{\cdot} + Cl_2 &\longrightarrow HCl + Cl{\cdot} \end{aligned}\right\} \quad . \quad . \quad . \qquad (15)$$

---

[41] Szwarc, *J. Chem. Phys.*, 1955, **23,** 204.

[42] Sheppard, Ph.D. Thesis, Massachusetts Institute of Technology, 1954.

[43] Bickel and Kooyman, *Rec. Trav. chim.*, 1952, **71,** 1137.

[44] Pease and Walz, *J. Amer. Chem. Soc.*, 1931, **53,** 3728.

This, for compelling reasons, has long since been replaced by the scheme:

$$\left.\begin{array}{lcl} Cl\cdot + CH_4 & \longrightarrow & CH_3\cdot + HCl \\ CH_3\cdot + Cl_2 & \longrightarrow & CH_3Cl + Cl\cdot \end{array}\right\} \quad . \quad . \quad . \quad 16)$$

It now seems probable that one should similarly replace the proposal that hydrogen atoms are displaced from aromatic molecules by the concept of radical addition followed by hydrogen abstraction as formulated in scheme (14).

B4. Attack by Radical Reagents on Hydrogen.—

$$R\cdot + H\text{–}C \longrightarrow R\text{–}H + \cdot C$$

This constitutes the normal reaction of radicals with saturated organic compounds and competes with radical addition in unsaturated compounds. Two aspects of the many results accumulated will be discussed here, namely, the competition between addition and attack on hydrogen in unsaturated compounds, and the position of attack in saturated compounds.

Although addition appears to be the normal rule in the first stage of radical attack in aromatic systems, this is not so if there is " allylic " hydrogen in the molecule. In such a case, there may be a fine balance in the choice between the two processes, depending on such factors as the reactivity of the radical, temperature, and the structure of the unsaturated compound. This is because attack on allylic hydrogen results in the displacement of a resonance-stabilised radical, whereas addition to a simple olefin usually leads to an unstabilised radical. Relatively subtle changes in the allylic system can totally alter the course of reaction. Thus, at 90° K hydroxyl radicals will add to the olefinic bond of methyl methacrylate or methacrylonitrile,[45] but will abstract allylic hydrogen from allyl alcohol.[46] Evidence for this contention is direct, since it depends on a study of the radicals themselves by electron-spin resonance spectroscopy. The radicals can be identified with little ambiguity by the characteristic hyperfine lines which appear in the electron-spin resonance spectra.

Kooyman and Farenhorst [47] have concluded that when $CCl_3\cdot$ radicals attack *cyclo*hexene addition and extraction of allylic hydrogen proceed at comparable rates. This reaction therefore represents a situation in which the various factors governing the alternative mechanisms just balance. Buckley *et al.*[48] have studied other systems in which these alternative reactions compete.

Radical attack on hydrogen in a saturated hydrocarbon chain can be remarkably selective. For example, most radicals will attack tertiary in preference to secondary or primary hydrogen in a paraffin hydrocarbon. Important factors include the dissociation energy of the C–H bond, the reactivities of the attacking and the displaced radical, temperature, and polar effects. The first two factors are tied together by another feature, namely,

---

[45] Ingram, Symons, and Townsend, *Trans. Faraday Soc.*, 1958, **54,** 409.

[46] Gibson, Ingram, Symons, and Townsend, *ibid.*, 1957, **53,** 914.

[47] Kooyman and Farenhorst, *Rec. Trav. chim.*, 1951, **70,** 867.

[48] Buckley, Leavitt, and Szwarc, *J. Amer. Chem. Soc.*, 1956, **78,** 5557 ; Buckley and Szwarc, *Proc. Roy. Soc.*, 1957, *A*, **240,** 396.

the extent of bond-breaking in the transition state. The more reactive the attacking radical, the smaller will be the bond-breaking in the transition state, according to the principle described by Hammond.[35] Hence for reactive radicals, the bond-dissociation energy and the stability of the displaced radical will be unimportant factors and the radical will be relatively unselective. For example, bromine atoms are more selective than chlorine atoms towards tertiary hydrogen.[49] As a general rule, the higher the temperature, the lower the power of selection of a given radical. Studies of the attack of hydroxyl radicals on a variety of organic compounds, including alcohols at 90° K, show that this very reactive radical is remarkably selective at this temperature.[45, 46] If Kenyon and Symons [50] are correct in assuming that the effective oxidising agent in strongly alkaline solutions of potassium permanganate is the hydroxyl radical, then it seems that, under certain circumstances, this radical is still quite selective at room temperature. They found that carboxylate ions containing tertiary hydrogen α or γ to the carboxyl group were preferentially attacked at the tertiary hydrogen atom. Attack on α-hydrogen is favoured by the fact that the resulting radical-ion is resonance-stabilised and it is therefore somewhat surprising that the attack was on γ-hydrogen when this was tertiary. However, it can be deduced by analysis of the hyperfine splitting due to the hydrogen nuclei in radicals such as $\cdot CMe_2\cdot OH$ that structures such as $H\cdot\ CH_2{=}CMe\cdot OH$ contribute considerably to the ground state of the radical, and stabilisation resulting from such hyperconjugation must outweigh the stabilising effect of the carboxyl group.

When hydroxyl radicals attack alcohols at low temperature α-hydrogen atoms are preferentially lost,[46] to give radicals of type $\cdot CR_2\cdot OH$ which must be stabilised to some extent by π-bonding between carbon and oxygen. Such overlap should also make radicals such as $\cdot CR_2Cl$ and $\cdot CR_2\cdot CO_2H$ relatively stable, and therefore it is remarkable that, when carboxylic acids and alkyl chlorides are attacked by chlorine atoms, α-hydrogen atoms are selectively avoided. However, methyl radicals selectively attack α-hydrogen in such compounds.[51] Russell and Brown [52] have explained these differences in terms of the electrophilic or nucleophilic character of the attacking radical. Thus, chlorine atoms are strongly electrophilic and hence hydrogen α and β to chlorine in alkyl chlorides will be deactivated towards attack by chlorine atoms. In contrast, methyl radicals are relatively nucleophilic and hence electron-withdrawal by chlorine or carboxyl favours attack on α-hydrogen.

Some idea of the geometry of the transition state in hydrogen-atom abstractions comes from the observation that the rates of attack on hydrogen by chlorine in a series of compounds R_3CH are remarkably independent of the size of substituents R. This result fits in well with the concept that the H–Cl bond is hardly formed in the transition state. One can also conclude

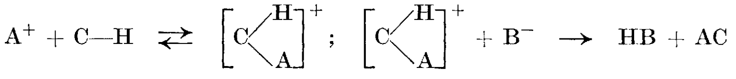
[49] Russell and Brown, *J. Amer. Chem. Soc.*, 1955, **77**, 4025.
[50] Kenyon and Symons, *J.*, 1953, 3580.
[51] Kharasch and Gladstone, *J. Amer. Chem. Soc.*, 1943, **65**, 15.
[52] Russell and Brown, *ibid.*, 1955, **77**, 4578.

that the angle between carbon, hydrogen, and chlorine is not far removed from 180° in the transition state (cf. section B6).

B5. Attack by Electrophilic Reagents on Carbon.—

$$A^+ + C\text{–}H \rightarrow A\text{–}C + H^+$$

Because of the very large free energy of the bare proton, this reaction will never occur as such. Indeed, it is even less likely than the direct displacement of hydride ion or a hydrogen atom. It is necessary once again to invoke a two-stage process for reactions involving electrophilic attack on carbon :



(IV)

(17)

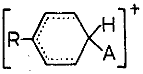
and hence the step involving C–H bond breakage appears as a nucleophilic attack on hydrogen. Since many solvents are good proton-acceptors, this second stage usually involves proton donation by the intermediate (IV) to the solvent ; that is, (IV) behaves as a strong acid. It might be argued that a termolecular, one-stage process adequately describes reactions of this type, and there is little direct evidence concerning the relatively subtle difference implied. However, since the polarity of most C–H bonds is such as to make hydrogen either slightly negative or neutral [53, 54] and since the polarisability of the C–H bond is small,[55] solvent molecules will not be oriented in the required direction for nucleophilic attack to occur simultaneously with the addition of A^+. One can again recall that when an electrophile attacks the C–H bond in a saturated molecule, it becomes linked to hydrogen rather than to carbon ; since the transition states for attack by A^+ on carbon and hydrogen are probably similar (see section B6), the preferential choice of hydrogen in the aliphatic case and of carbon in the aromatic case is most readily understood if one postulates the formation of a relatively stable intermediate in the aromatic case only. Therefore, this section will be confined to a discussion of evidence relating to the formation and stability of such intermediates during electrophilic aromatic substitution.

Since Melander's discovery that there is no detectable isotope effect during several electrophilic substitutions of tritium-labelled aromatic compounds,[56, 37] a variety of studies has been made, confirming Melander's results and extending the study to other reagents. In several instances, definite isotope effects have now been detected.[57, 58, 59, 60] Taken in isolation, this work gives little information regarding the formation of stable

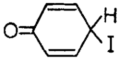
---

[53] Gent, *Quart. Rev.*, 1948, **2**, 383.
[54] Glazer and Reiss, *J. Chem. Phys.*, 1955, **23**, 1937.
[55] Le Fèvre and Le Fèvre, *Chem. and Ind.*, 1955, 1121.
[56] Melander, *Acta Chem. Scand.*, 1949, **3**, 95.
[57] Berglund-Larsson and Melander, *Arkiv Kemi*, 1953, **6**, 219.
[58] Bonner and Wilkins, *J.*, 1955, 2358.
[59] Zollinger, *Helv. Chim. Acta*, 1955, **38**, 1597, 1617.
[60] Grovenstein and Kilby, *J. Amer. Chem. Soc.*, 1957, **79**, 2972.

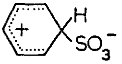
intermediates since it may relate only to the degree of breaking of the C–H bond in the transition state. It is noteworthy, however, that in all systems showing a positive isotope effect the intermediate complex (V) can readily lose a proton from R or A to give a neutral molecule or zwitterion, which is bound to be a far weaker acid than the original complex. (The proton lost by R or A is attached to nitrogen or oxygen and would be lost more readily than the proton attached to carbon.) Thus, in the iodination of phenol [60] the neutral intermediate would be (VI) and in sulphonation (VII). It is



(V)



(VI)

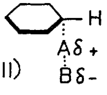


(VII)

concluded that these results are consistent with the view that a relatively stable intermediate is formed during electrophilic aromatic substitution; and that the transition state of highest energy normally lies between the reactants and an intermediate which behaves as a strong acid; but that when this intermediate is electrically neutral it may become so weak an acid that the transition state for the step involving loss of this proton may be of higher energy than that for the step involving addition of the electrophile. It is not easy to see how the results may be fitted to any other scheme.

The concept that an intermediate of structure (V) is formed as an essential stage in aromatic electrophilic substitution does not mean that the transition state must closely resemble this intermediate, although this assumption is often made. Indeed, since many such substitution reactions are effected by reagents which are not free in the sense implied in reaction (17), but are still bonded, albeit weakly, to some nucleophile, one would expect that the transition state for the first stage of this reaction could be very different from the complex (V). If the " source " of A^+ be depicted as AB, the transition state might be represented as (VIII). How close (VIII) comes to (V) depends on a variety of factors amongst which the strength of the A–B bond must be important. Brown *et al.* have given evidence which points strongly to this conclusion in their studies of the Friedel–Crafts reaction,[61, 62, 63] and it has been elegantly established by Corey and Sauers [64] for the ionisation of certain arylalkyl toluene-*p*-sulphonates.

(VIII)



The most direct way of establishing the formation of an intermediate during a chemical reaction is to devise conditions under which the intermediate is sufficiently stable to be studied by spectroscopic or other means. Perhaps the simplest of all electrophilic aromatic substitutions is acid-catalysed hydrogen exchange. The intermediate for this reaction would have the symmetrical structure (IX). In weakly acidic media such an

---

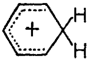
[61] Brown and McGary, *J. Amer. Chem. Soc.*, 1955, **77**, 2300.

[62] Brown and Jungk, *ibid.*, p. 5579.

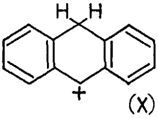
[63] Brown, *ibid.*, p. 5584.

[64] Corey and Sauers, *ibid.*, 1957, **79**, 248.

intermediate could have only transitory existence, but with increasing acidity, and (equally important) with decreasing basicity of the medium, the concentration of the intermediate should greatly increase. Reid has shown that aromatic hydrocarbons, including benzene, dissolved in liquid hydrogen fluoride containing boron trifluoride, give compounds whose visible and ultraviolet spectra are consistent with formulation (IX).[65, 66] The case for anthracene is stronger since, as has been pointed out,[67] protonation could give the ion (X) which is structurally similar to the carbonium ion Ph_2CH^+ formed from diphenylmethanol by reaction with sulphuric acid.



(IX)



(X)

In fact, the visible and the ultraviolet spectra of anthracene and diphenylmethanol in sulphuric acid are almost identical. When 1 : 1-diphenylethylene reacts with sulphuric acid, the carbonium ion $^+CPh_2Me$ is formed. The main visible band for this ion is shifted 17 mμ to shorter wavelengths relative to that for $^+CHPh_2$. If formulation (X) is correct for protonated anthracene, the spectrum for protonated 9-methylanthracene should show a similar shift relative to protonated anthracene. This prediction has been confirmed,[68] the shift being 16 mμ to shorter wavelengths.

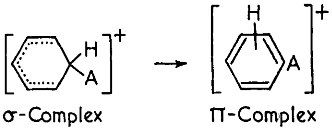
(Although not directly relevant to this Review, reference ought to be made to the important discovery that certain polynuclear hydrocarbons, including anthracene, with sulphuric acid form paramagnetic substances which are almost certainly monopositive ions formed by loss of π-electrons. This conclusion comes directly from a study of the hyperfine lines recorded in the electron-resonance spectra of these solutions. Some confusion has arisen as a result of this discovery, but it can readily be demonstrated that either protonated anthracene or anthracene positive ions can be prepared in sulphuric acid depending on the conditions, and therefore the electron-resonance results in no way invalidate the arguments made regarding protonation.)

Finally, some reference ought to be made to the concept of π-complex formation. This has become an accepted way of describing certain loose complexes between donor and acceptor molecules where no specific σ-bonding exists. It is probable that in most cases the term " charge-transfer complex " would be equally suitable. Outstanding features seem to be that the interaction energy is small, that the complexes are not very sensitive to structural modification, and that they usually give rise to characteristic absorption spectra in the visible or near-ultraviolet region. A discussion of these complexes is relevant here, since it is quite possible

---

[65] Reid, *J. Amer. Chem. Soc.*, 1954, **76**, 3264.
[66] Cf. Muller, Pickett, and Mulliken, *ibid.*, p. 4770.
[67] Gold and Tye, *J.*, 1952, 2172.
[68] Grace and Symons, unpublished results.

that an important step in electrophilic aromatic substitution comprises a unimolecular change from a classical σ-complex to a π-complex:



Such complexes may be formed during the initial and the final stage of acid-catalysed hydrogen exchange, and Gold and Satchell [69] have presented kinetic results which, they claim, can best be understood in terms of a slow step in which a loose " outer " complex is converted into an intermediate of type (IX). This conclusion is based primarily on the fact that the rates follow Hammett's acidity function H_0 rather than the hydrogen-ion concentration. Long and Paul [70] have suggested that the simpler alternative in which proton-transfer is the rate-determining step is equally compatible with the kinetic results : this seems doubtful since the transition state from proton-donation by the conjugate acid of the solvent would closely resemble the transition state for proton-removal by solvent in reactions such as the acid-catalysed enolisation of ketones, which follow C_{H^+} rather than H_0.

If π-complex formation between aromatic compounds and proton is important, one might hope to be able to establish their presence by spectrophotometric studies. Evans *et al.*[71] have postulated that the intense bands in the 600 mμ region observed for certain 1 : 1-diarylethylenes in weakly acidic media are the result of π-complex-formation between protons and the olefinic bond. However, similar spectra are recorded when such compounds as diphenylmethanol are dissolved in the same solvents and, for this and other reasons, it seems unlikely that this simple explanation is correct.[68]

B6. Attack by Electrophilic Reagents on Hydrogen.—Electrophilic attack on hydrogen, resulting in the so-called " hydride-transfer reaction ", is influenced in a predictable way by inductive and resonance effects. An extreme form of combined inductive facilitation of the reaction and resonance-stabilisation of the product is found in the hydride-transfer from the addition products of unsaturated molecules to anionic nucleophilic reagents. These are discussed in section B1 since the attack of the nucleophile on carbon is so essential. We shall discuss here the reactions in which the role of an electrophile is conspicuous.

The reaction (18), together with its variation with different charge types, is the essential step in the reactions to be discussed here. Clearly the reaction can be favoured by increasing the electron-availability in R_3CH, by

$$R_3CH + A^+ \longrightarrow R_3C^+ + HA \qquad . \quad . \quad (18)$$

making A^+ more electrophilic, and by having particularly stable R_3C^+ or HA. Since in nearly all cases the reactions also appear to be reversible,

---

[69] Gold and Satchell, *J.*, 1955, 3609, 3619, 3622.
[70] Long and Paul, *Chem. Rev.*, 1957, **57**, 935.
[71] Evans, Jones, and Thomas, *J.*, 1956, 2757.

assistance can also be given by further reactions which remove the products. It will be appropriate to discuss these factors for a particular reaction, the use of alcohols as a source of hydride ions, shown in reaction (19).

$$A^+ + R_2CH{\cdot}OH \longrightarrow AH + R_2C{=}^+OH \qquad . \quad . \quad (19)$$

The subsequent reaction in this case is the loss of a proton from the conjugate acid of the ketone $R_2C{=}^+OH$. Although study of the reaction in acidic media, by Bartlett and McCollum,[72] shows the requirement for a reasonably strongly electrophilic A^+, the triphenylmethyl cation reacted with *iso*propyl alcohol about a thousand times faster than the sterically similar but much less electrophilic tri-*p*-methoxyphenylmethyl cation. The same work showed that the electron-releasing methyl group of the alcohol favoured the reaction : methanol was unreactive and *iso*propyl alcohol reacted about ten times faster than ethanol, a reactivity further complicated by varying extents of conversion into the unreactive conjugate acid. The reversibility of this reduction of carbonium ions by alcohols was also demonstrated by reduction of acetone to *iso*propyl alcohol by di-*p*-methoxyphenylmethanol.

The reduction of triphenylmethyl chloride by ether in the presence of aluminium chloride [73] and the reactions of other ionised triphenylmethyl esters with *cyclo*heptatriene to produce [74] the tropylium (tropenium) ion ($C_7H_7{}^+$) are both further examples of reactions facilitated by the stability of the product.

A more extreme example [75] of the inductive facilitation of hydride-transfer is seen in the reaction (20) of alkoxide ions with ketones, where equilibrium is readily attained by a hydrogen-transfer mechanism. Inter-

$$R_2CH{\cdot}O^- + R'_2CO \rightleftarrows R'_2CH{\cdot}O^- + R_2CO \qquad . \quad . \quad (20)$$

mediate between this reaction of the carbonyl compound and the alcohol conjugate base and that of the previously mentioned neutral alcohol with the conjugate acid of the ketone is the Meerwein–Ponndorff reaction, where the aluminium alkoxide reduces the aluminium complex of the ketone. The Tishchenko reaction, an aluminium alkoxide version of the Cannizzaro aldehyde disproportionation, is also presumably a manifestation of the amphoteric nature of aluminium alkoxides.

Hydride-transfers to or from the analogues in the ammonia system of the alcohols and carbonyl compounds appear to be involved in the Leuckart reduction of ketones by ammonium formate [76] and the reduction of hexamethylenetetramine by its *N*-alkyl derivatives, the Sommelet Reaction.[77]

The apparently analogous biochemical transamination which equilibrates an amino-acid with a ketone, however, is a prototropic shift in the Schiff base, not a hydride-transfer.

---

[72] Bartlett and McCollum, *J. Amer. Chem. Soc.*, 1956, **78,** 1441.

[73] Norris, *Org. Synth.*, Coll. Vol. I, 1941, p. 548.

[74] Dauben, Gadecki, Harmon, and Pearson, *J. Amer. Chem. Soc.*, 1957, **79,** 4557.

[75] Doering and Aschner, *ibid.*, 1953, **75,** 393.

[76] Moore, in " Organic Reactions ", John Wiley and Sons, New York, 1949, Vol. V, p. 301.

[77] Angyal, *op. cit.*, 1954, Vol. VIII, p. 197.

An interesting example of hydride-transfer in a strongly basic oxygen-free system is the reaction (21), showing surprising specificity of the electrophilic triphenylboron for hydrogen, rather than for the presumably more basic but larger carbanion.[78]

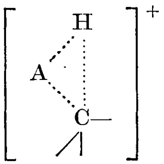
$$\mathrm{Ph{\cdot}CHNa{\cdot}CH_2{\cdot}CH_2{\cdot}CHPhNa + 2Ph_3B \longrightarrow Ph{\cdot}CH{:}CH{\cdot}CH{:}CHPh + 2NaPh_3BH} \qquad (21)$$

The intermolecular hydride-transfer producing an ordinary carbonium ion was first described by Bartlett, Condon, and Schneider.[79] They showed that an extremely rapid exchange of halogen and hydrogen occurred when a tertiary halide and *iso*alkane were mixed in the presence of aluminium bromide. The significant step is the reaction (22), and the rate was immeasurably large. This important paper immediately led to an improved understanding of the reactions of hydrocarbons in strongly acidic systems.

$$\mathrm{R^+ + R'H \longrightarrow RH + R'^+} \quad . \quad . \quad . \quad . \quad (22)$$

The types of intramolecular analogues to reaction (22) are known. One, familiar for many years, is the 1 : 2-hydride shift related to rearrangements of the carbon skeleton of the Whitmore type ; an example is the formation of *tert.*-butyl derivatives in reactions of *iso*butyl halides with Lewis acids. Of the second type are hydride-transfers from carbon to a more remote part of the molecule. One is the 1 : 3-shift detected in the carbonium ion resulting from the solvolysis of norbornyl compounds.[80] The " transannular reaction " accompanying ionisation in cyclic compounds of medium ring size are also examples of the attack of carbonium ions on a C–H bond in the same molecule.[81] This type of reaction has been found more frequently now that analytical procedures for minor products have improved.

The mechanisms of hydride-transfer must of course differ in detail among the various types. It appears, nevertheless, that some generalisations of wide application can be made. In all cases an electrophilic reagent attacks the C–H bond, and the reasonable mode of attack is on the electrons of the bond. A triangular transition state (XI) for reaction (18) is therefore proposed.



(XI)

This mode of attack, a distinct contrast to the linear transition state B : H : C for nucleophilic attack on hydrogen, is also supported by a small value of the isotope effect observed for well-established hydride-transfer reactions. In the Cannizzaro reaction,[82] in the rearrangement of the *n*-propyl cation accompanying the action of nitrous acid on *n*-propylamine,[83] and in the carbonium ion–alcohol reaction,[72] isotope effects of the order of 2 or less were observed. Similarly, small effects are found in the hydride-

---

[78] Witting and Stilz, *Annalen*, 1956, **598,** 85.

[79] Bartlett, Condon, and Schneider, *J. Amer. Chem. Soc.*, 1944, **66,** 131.

[80] Roberts, Lee, and Saunders, *ibid.*, 1954, **76,** 4501.

[81] Prelog and Schenker, *Helv. Chim. Acta*, 1952, **35,** 2044 ; Cope, Fenton, and Spencer, *J. Amer. Chem. Soc.*, 1952, **74,** 5844 ; and later work from both laboratories.

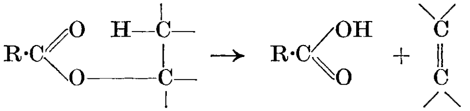
[82] Wiberg, *ibid.*, 1954, **76,** 5371.

[83] Shiner, personal communication.

transfer from triphenylsilane[84] and from the diphenylborane–pyridine complex.[85] The triangular transition state leads to the expectation of a small isotope effect, since large isotope effects can only arise from a loss of the stretching vibration in the transition state. The converse statement, that a small isotope effect requires a non-linear transition state, is false; however, non-linearity is one of a number of factors which can lead to small isotope effects. A more complete discussion of the argument leading to the conclusion of a triangular transition state is found in a paper by Hawthorne and Lewis,[85] with special reference to a boron–hydrogen bond.

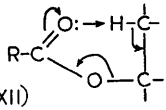
B7. Unimolecular Reactions with Intramolecular Assistance.—The unimolecular transfer of hydrogen from one atom to another in the same molecule, often accompanied by other electronic shifts, is almost certainly facilitated by the formation of a new bond to hydrogen. We therefore classify these reactions as assisted cleavages, without specifying the nature of the attacking reagent. The most familiar examples are reactions of high activation energy and are frequently pyrolyses.

Typical are the pyrolytic eliminations from esters shown in reaction (23). The mechanism was indicated by the observation of first-order kinetics and stereospecific *cis*-elimination.[86, 87] The elimination follows the

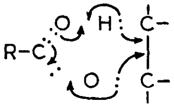


. . . (23)

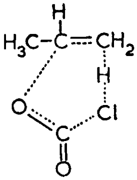
Hofmann rule,[87] showing that contributions of olefinic structures to the transition state are not very important. The transition state involving a six-membered ring suggested by the conformation written in reaction (23) is not demonstrated; the four-membered ring using only one oxygen is also possible. The reaction can be represented as a nucleophilic attack on



(XII)



(XIII)



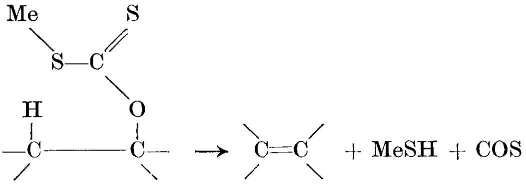
(XIV)

hydrogen according to the scheme (XII), but the direction of motion of electrons is undemonstrable and the same result can be attained by the alternative radical-like scheme (XIII). Inability to distinguish schemes such as these experimentally is the source of our failure to classify these reactions as nucleophilic, electrophilic, or radical attack on hydrogen or carbon.

---

[84] Kaplan and Wilzbach, *J. Amer. Chem. Soc.*, 1955, **77**, 1300.
[85] Hawthorne and Lewis, *ibid.*, in the press.
[86] Barton, *J.*, 1949, 2174.
[87] Bailey and King, *J. Amer. Chem. Soc.*, 1955, **77**, 75.

A mechanistically similar but easier reaction occurs when *O*-alkyl *S*-methyl xanthates are heated (reaction 24):



(24)

In this case the ring size is clear, since the compound has greatly enhanced reactivity compared with a carbonate, but it is not clear which sulphur atom is involved. The immediate product of the reaction with the alternative arrangement of atoms, the *S*-methyl dithiocarbonate, is certainly unstable under the reaction conditions. Pyrolysis of *iso*propyl chloroformate in the gas phase yields a substantial amount of propene, and the first-order rate law observed led to the proposal of the transitions state (XIV) for this reaction.[88] However, recent further studies have led to the suggestion that an ionic intermediate may be involved.[89] Ion pairs have been proposed as intermediates in the pyrolysis of alkyl chlorides on the basis of the effect of substituents on the reaction rate,[90] although on pyrolysis some alkyl halides react by radical paths. Cyclic non-polar mechanisms have less chance of competing with ionic reactions in solution, and there are very few reactions with C–H bond breakage for which this cyclic unimolecular mechanism has been established. In at least one case there is a suggestion of the occurrence of this mechanism. For decomposition of 1-methylbutyl chlorosulphite in dioxan solution an ionic mechanism has been established; but in 2 : 2 : 4-trimethylpentane solution the reaction is slower, there is more olefin produced, and a very large retardation by β-deuterium suggests the possibility that the C–H bond may be broken in the rate-determining step of this first-order reaction. Confirmation is found in the preliminary result that the reaction involves predominant but not complete *cis*-elimination.[91]

The above reactions show close resemblance to ionic reactions. Some reactions conveniently classified here appear to resemble radical reactions more closely. Thus the formation of methane from the photolysis of acetaldehyde is not entirely suppressed by addition of iodine.[92, 93] The residual reaction must be the one-step non-chain process (25):

$$CH_3{\cdot}CHO + h\nu \longrightarrow CH_4 + CO \qquad (25)$$

This primary process requires a substantial energy imput since it occurs [94] on irradiation with light of 2537 Å but not of 3130 Å. Presumably other

---

[88] Choppin and Compere, *J. Amer. Chem. Soc.*, 1948, **70**, 3797.
[89] Lewis and Herndon, unpublished work.
[90] Ingold, *Proc. Chem. Soc.*, 1957, 279.
[91] Duffey, M.A. Thesis, The Rice Institute, 1955.
[92] Gorin, *Acta Physicochim. U.S.S.R.*, 1938, **9**, 681.
[93] Blacet and Loeffler, *J. Amer. Chem. Soc.*, 1947, **64**, 893.
[94] Blacet and Heldman, *ibid.*, 1942, **64**, 889.

such reactions accompany dissociation into radicals in photolytic and possibly electron-impact reactions, but they do not appear important in thermal reactions at ordinary temperatures.

Conclusions

Cleavage of carbon–hydrogen bonds is a common and important reaction of organic compounds. Except for the rare types listed in section A, this breakage will only occur on attack of a reagent on hydrogen. The bond is sufficiently strong to require the contribution of new bond formation to the transition state for cleavage to occur; to this extent, our classifications B1, B3, and B5, which are attacks on carbon, represent non-existent mechanisms. However, all the examples in these classifications have unsaturated or aromatic reactants, and important help to the bond cleavage is given by prior addition of a reagent to the unsaturated system. Thus hydride-loss is greatly assisted by prior addition of a nucleophile, even though an electrophile is needed to accept the hydrogen. Similarly, aromatic substitution by radical or electrophilic reagents needs another radical or a nucleophile respectively to complete the reaction, but prior addition is also an important step. As a consequence of this generalisation, one can expect that removal of hydrogen bonded to a *saturated* carbon atom will always involve immediate attack on the hydrogen atom.