

REACTIVE INTERMEDIATES
IN
ORGANIC CHEMISTRY

N. S. ISAACS

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Preface

Physical organic chemistry is a remarkably ill-defined subject; witness the almost complete lack of overlap in the subject matter covered in four recent text books with that title. The physical principles of organic chemistry are now universally taught at the university level; nevertheless it would seem that there is a wide diversity in the approach to the subject.

This book is an attempt to present physical organic chemistry from the point of view of reactions, but with strong emphasis on physical principles which are separately discussed. Furthermore the organization is such as to draw together reactions taking place via a common type of reactive intermediate and thus the emphasis is upon the chemistry of these important and often controversial species. This has the advantage of enabling topics such as aromatic electrophilic substitution, olefin addition and superacid chemistry to be treated under one heading, and to discuss their common characteristics as carbonium ion reactions.

All methods of subdividing an integrated subject such as organic chemistry must have disadvantages, however, and in the present treatment the reader will have to seek information on substitution at the aromatic ring under some five separate headings according to the type of intermediate involved. The inconvenience thus caused should be compensated by thorough indexing and full cross-referencing.

This book treats only reactions which proceed by way of reactive intermediates; single-step reactions are included where appropriate (e.g. nucleophilic aliphatic substitution and polar eliminations) to contrast the characteristics with related multistep processes. In scope it is intended for the undergraduate rather than the specialist but includes material somewhat beyond most degree courses for those interested in the subject.

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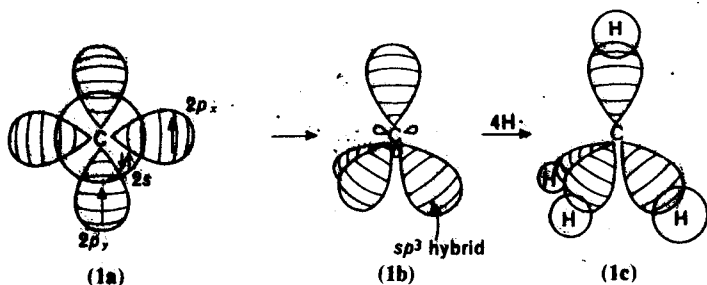
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Chapter 1

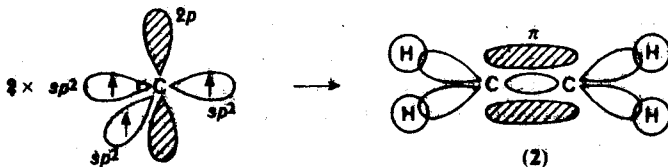
Physical Principles of Organic Chemistry

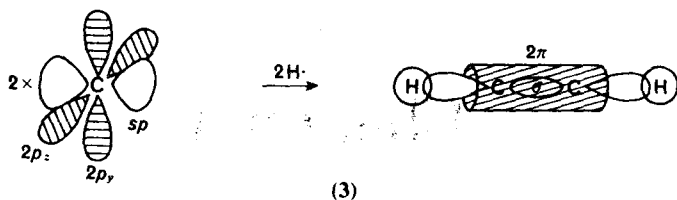
1.1 THE VALENCE STATES OF CARBON

The normal state of combination of carbon is tetravalent and this is brought about by the pairing of each of the valence electrons ($2s^2$ and $2p^2$) with four electrons provided by the ligands. In the saturated, tetrahedral form characteristic, say of methane, this is accomplished by the 'hybridization' of the carbon atomic orbitals (1a) to a set of four equivalent orbitals, denoted sp^3 (1b), each of which overlaps with a $1s$ orbital of a hydrogen atom (1c). The result is four localized two-electron bonds set as far apart from each other as is



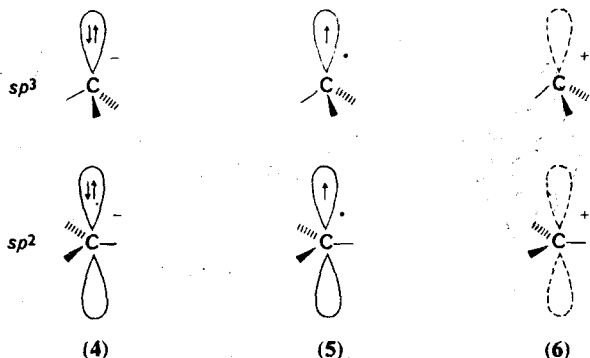
geometrically possible. By alternative hybridization schemes, sp^2 and sp , trigonal and digonal bonding arrangements may be realized, one and two $2p$ orbitals being retained for π -bond formation as in ethylene (2), and acetylene (3), respectively. In each of these states, carbon exhibits a formal tetravalency



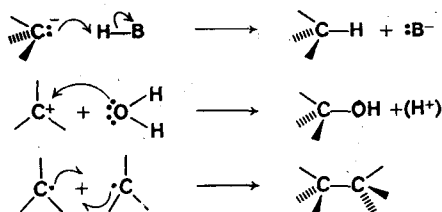


and a filled octet of valence electrons. Other, less usual, valence states of carbon may be formed in reactions, but are transient high-energy species which tend to revert rapidly to the tetravalent state. Species containing these unusual valence states are some of the reactive intermediates which form the subject of this book.

Trivalent carbon is well established. If three ligands are attached to a central carbon atom by two-electron σ -bonds, the remaining orbital may hold two, one or no electrons; no other possibilities are permitted. This results in the formation of a carbanion (4), a free radical (5), and a carbonium ion (6),

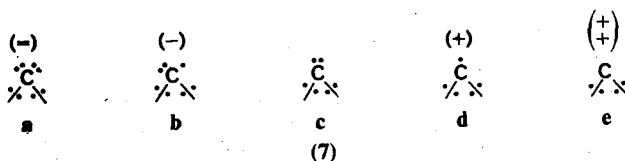


respectively, with formal charges of -1 , 0 and $+1$. In principle we may describe the structures of these species using sp^3 or sp^2 hybrid orbitals, which will produce either a pyramidal or a planar geometry. Of these three types of trivalent carbon, only the carbanion has a filled octet. The radical and the carbonium ion are both electron deficient. In its chemistry, the carbanion tends to be an electron-pair donor (a nucleophile), the carbonium ion an electron-pair acceptor (an electrophile), and the radical tends to react with other unpaired electron species and form a new two-electron bond.

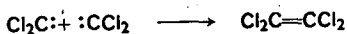


The double-barbed arrow \curvearrowright signifies the movement of an electronpair, and the singly-barbed arrow \frown the movement of an unpaired electron.

Divalent carbon compounds are also known. Some of the possible forms these could take are shown in 7. However, it seems that only the neutral form

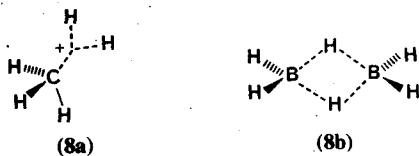


(7c), has any existence which has so far been discovered. Compounds with two covalent bonds and an unshared pair at carbon are known as carbenes (methylenes) and many members of this family are believed to be formed very transiently in certain reactions (Chapter 6). Carbenes will react with almost anything and, if nothing better is available, will dimerize;



Monovalent carbon compounds such as $\text{R}-\text{C} \cdot$ may be formed very transiently in high-temperature reactions (e.g. flames, electric discharges) but not apparently in reactions occurring under more mild conditions.

Pentavalent carbon is traditionally considered to be energetically impossible since the bonding would require bringing in high-lying carbon $3s$ orbitals. Very recently this view has had to be modified since it now appears that pentavalent cations of carbon, e.g. CH_5^+ (8a), may be involved in very acidic media. The subject is discussed further (Section 2.30). It is unlikely that bonding involves higher atomic orbitals of carbon, and a three-centre two-electron bond as in B_2H_6 (8b) is assumed.



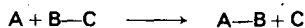
The bonding discussed above refers to the lowest (ground) electronic states. All molecules may in principle be promoted to an excited electronic state by absorption of a quantum of radiation of the appropriate energy. This results in the reorganization, in the main, of the highest lying valence electrons.

1.2

THE ENERGETICS OF REACTIONS

Chemical reactions are the spatial reorganizations of atoms and of the valence electrons which constitute covalent bonds. Except in the case of photochemical reactions, only the lowest (ground) electronic state of the reagents is involved and the passage from the reagents to the products may be considered to take place in a continuous fashion. Thus at any intermediate stage during the progress of a reaction, it is possible in principle to describe the reacting system in terms of its energy, the coordinates of all the atoms and so on. The progress of the reaction can then be mapped on a multidimensional 'surface'; the most favourable pathway, the 'reaction coordinate', will be that which requires the system to acquire the least amount of potential energy along the route. In real terms, the problem of determining (by calculation) the potential energy surface of a multi-atom system is an immensely difficult task in computation and only recently have solutions for quite small systems been attempted. However, the concept of a reaction coordinate is qualitatively useful and can aid our understanding of reaction mechanisms.

Consider the case of the simple exchange reaction:



If the three atoms retain a linear arrangement throughout, the only coordinate variables are the internuclear distances A, B and B, C. A three-dimensional graph of these two variables plotted against the third, potential energy, can be represented in two dimensions by drawing contours of equal energy (Figure 1a). It will be noticed that there is a relatively easy route from initial to final states along the energy 'valley' a-b, over the saddle-point b, and finally by descent through the valley b-c, in analogy with the map of a mountain pass. If we plot the potential energy of this route, which is the reaction coordinate, against some measure of progression along it, a curve such as Figure 1b is obtained. This indicates that even in the most favourable circumstances the reacting system must acquire potential energy in order to react, this process being known as 'activation'. The minimum amount of energy required, the 'activation energy', is the difference between the energies of the initial or reagent state, a, and the saddle-point, b, which is known as the 'transition state'. This energy is supplied to the reacting molecules as thermal energy—kinetic,

PHYSICAL PRINCIPLES OF ORGANIC CHEMISTRY

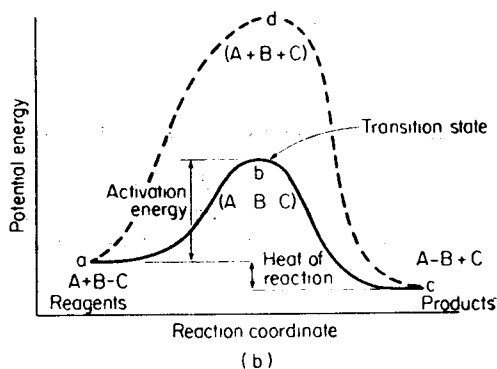
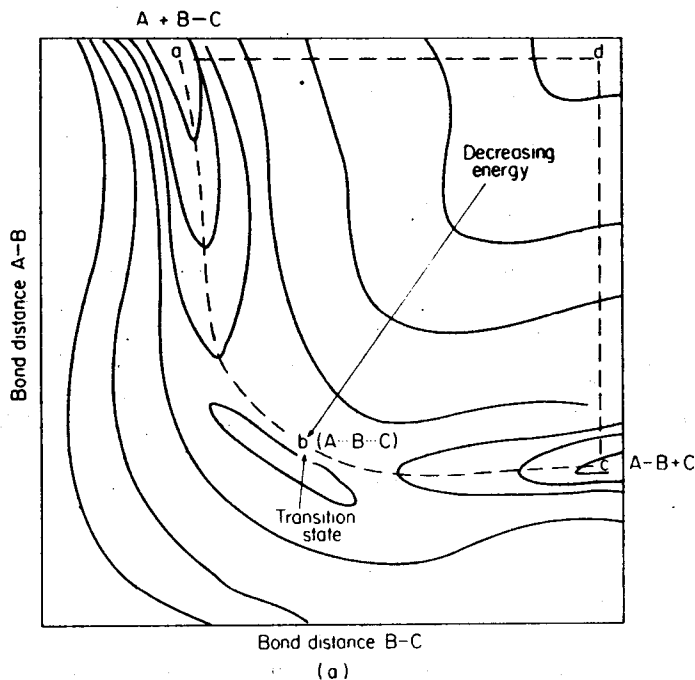
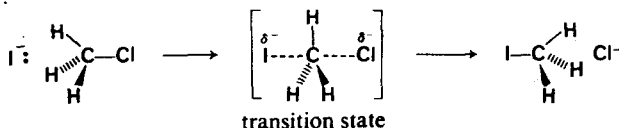


Figure 1. (a) Schematic potential energy surface for a simple displacement reaction; (b) reaction pathways for the concerted reaction (solid line) and non-concerted reaction (dashed line).

vibrational and rotational energy of the reactants. At any instant, only a small fraction of molecules will possess sufficient energy to surmount the potential barrier to reaction. It can be seen that any pathway other than the reaction coordinate between reagents and products will require an even greater amount of activation and will therefore be less favourable. For instance, compare the pathway a-d-c (Figure 1b) by which the B—C bond is first broken and then the A—B bond formed in two separate steps. The activation energy is much larger. It appears, in this case at least, that reaction occurs by a *concerted* bond making and bond breaking, that the energy released by the former in part compensates for the energy required by the latter. The net reaction is exothermic, the heat of reaction being the difference in energy between reagents and products. Another point to note is that the most favourable pathway from between *products* back to *reagents* is the same reaction coordinate; information on the course of a reaction in one direction is therefore applicable for the reverse reaction. This is known as the 'Principle of microscopic reversibility'. A potential energy diagram of this type would be applicable to a displacement reaction at a saturated carbon, such as:

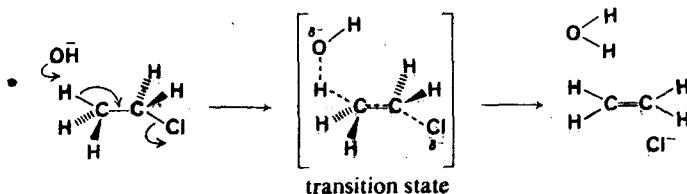


We know that activation energy is required for almost all chemical reactions to occur, since their rates increase with temperature. At higher temperatures, a greater proportion of the reactants will possess the necessary kinetic energy to pass over the activation barrier.

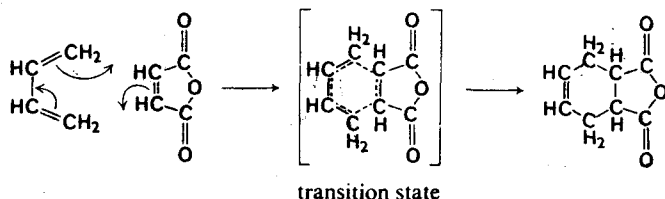
1.3

SIMPLE AND COMPLEX REACTIONS

The reaction discussed above was characterized by a single activation barrier along the reaction coordinate and may be designated a 'concerted' reaction. Many common reactions are of this type even though they may involve large molecules and the formation and breaking of several covalent bonds, for example in β -elimination:

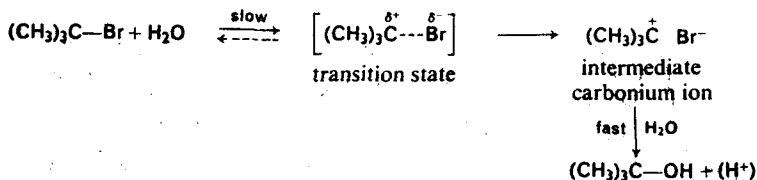


and in the Diels-Alder reaction:

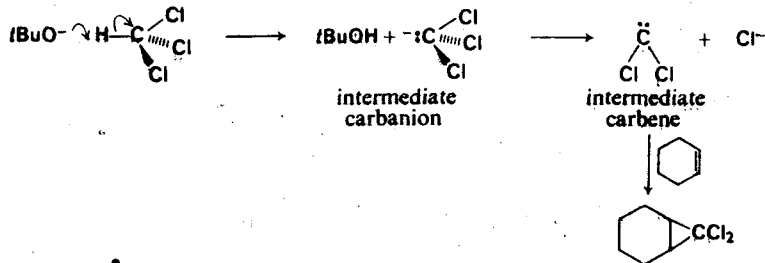


On the other hand, many organic reactions are more complex in the sense that the reaction coordinate has more than one energy maximum and consequently one or more *reactive intermediates* represented by an energy minimum (Figure 2d-i), but nonetheless a high-energy species with respect to reagents and products. A reactive intermediate has some stability with respect to small displacements along the reaction coordinate unlike a transition state which is unstable. An intermediate may be represented by a conventional valence-bond structure (or series of structures) whereas a transition state must often be represented with partly formed bonds. Intermediates have a finite lifetime which under appropriate conditions may extend to isolation as a stable species. The lifetime of the transition state of a reaction is exceedingly short, probably of the order of a period of vibration (ca 10^{-13} s). Some examples of reactions which proceed via one or more reactive intermediates are given below and will be discussed in more detail in later chapters. Further schematic reaction coordinate diagrams are given in Figure 2.

Tertiary halide hydrolysis



Base decomposition of chloroform



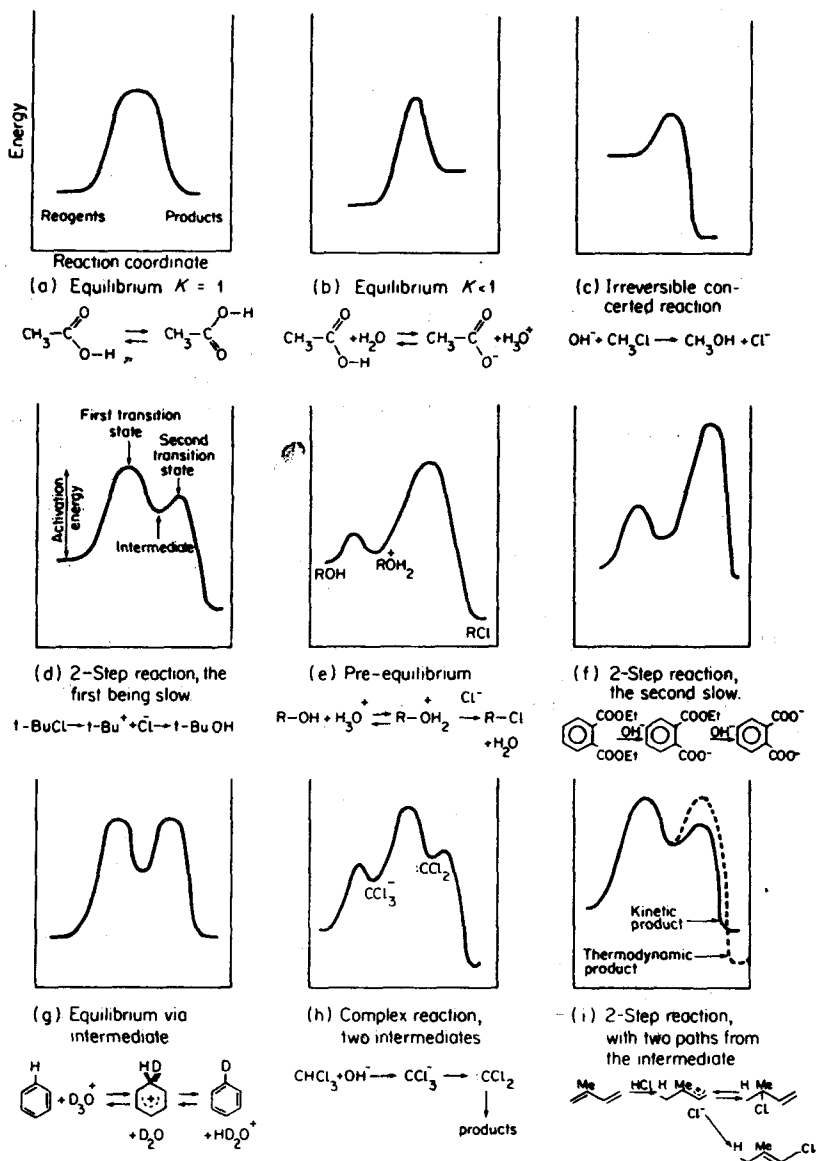


Figure 2. Schematic reaction pathways for various reaction types.