

## STUDY GUIDE FOR CHAPTER 4

1. Functional Groups – these are specific atoms or (more often) groups of atoms in the molecule, which largely determine the chemical behavior of the molecule (and the compound). According to their functional groups compounds are conveniently classified as *alcohols*, *amines*, *carboxylic acids*, *aldehydes*, *ketones*, *ethers*, *epoxides*, etc. Functional groups should be very well known and easily recognized!!
2. Nomenclature of Alkyl Halides – their functional group is a halogen atom, and they are accordingly classified as fluorides, chlorides, bromides and iodides. When naming them, one can adopt either of two different approaches:
  - A. The **functional class nomenclature** – a compound is named as a halide, i.e. a fluoride, chloride, bromide iodide. If the molecule is branched, the longest chain, starting at the carbon bonded to the halogen, is selected (and numbered from that atom).
  - B. The **substitutive nomenclature** (the truly systematic nomenclature!!) – the molecule is named as a substituted alkane, i.e. fluoroalkane, chloroalkane, etc. Halogens and alkyl groups, according to IUPAC, have equal rank, i.e. neither of them is treated preferentially when numbering the chain. Thus, as with alkanes, the numbering should be started from the terminus nearer to a substituent.
3. Nomenclature of alcohols – the functional group is the hydroxyl group (OH). Again, two different ways to name them exist and are practiced:
  - A. The functional class nomenclature – the compound's name consists of two words, the second of which is always alcohol. The first is the name of the alkyl group bound to the hydroxyl group. Thus, methyl alcohol, ethyl alcohol, etc. Works really well only for small molecules.
  - B. The substitutive nomenclature (Systematic nomenclature) – according to IUPAC, an alcohol name is derived from the name of the corresponding alkane by replacing the suffix *-ane* with the suffix *-ol*. Thus, ethane – ethanol, butane – butanol. In larger systems the position of the hydroxyl group has to be specified by number. The hydroxyl group outranks (has higher rank than) the alkyl groups or halogens. So numbering of a chain should start from the terminus closer to the hydroxyl group. In cyclic systems, in absence of any other, higher ranking groups (examples will be seen in later chapters), the hydroxyl group is assumed to be number 1, and is not numbered in the name.
4. Classification of alcohols and alkyl halides – this is done according to the type of carbon to which the hydroxyl group (or halogen) is bound:
  - A. Primary – if bound to a primary carbon;
  - B. Secondary – if bound to a secondary carbon;
  - C. Tertiary – if bound to a tertiary carbon;
5. Electronic Structure of Alcohols and Alkyl Halides – oxygen in the OH group and halogens (in alkyl halides) are all sp<sup>3</sup>-hybridized. Bonds to carbon are polar (because of higher electronegativity) causing the appearance of bond dipoles and (unless forbidden by symmetry!) molecular dipoles.
6. Physical Properties – these, as in any other case, are governed by the intermolecular attractive forces.
  - A. Boiling Points – the following attractive forces play role:
    - a. Dipole – dipole force – due to the significant molecular dipole moments. These cause increase of bp for both alkyl halides and alcohols in comparison with the corresponding isostructural alkanes.
    - b. *London* dispersion forces – they are still present, because of the hydrocarbon parts of these molecules.
    - c. Hydrogen bond – it is a very specific interaction of highly electron depleted H-atom (usually bound to O or N) and an O or N-atom of another molecule. It is a donor – acceptor type interaction, in which an O or N-atom donates a lone pair for partial bonding with highly electropositive H-atom. H-bonds are

much weaker than regular covalent bonds (about 10 times), but their effect is very significant, evidenced by the MUCH HIGHER bps of alcohols compared to those of alkyl halides, even though both classes of compounds have roughly equal dipole moments.

Boiling points of alkyl halides are influenced by two other factors:

- 1) Type of halogen – bps tend to increase with increased size of halogen. One reason is weight of atom, another is the so-called polarizability, i.e. the increased tendency of the molecule to generate an induced dipole.
- 2) Number of halogens – bps steadily increase with increased number of halogens. Reason – weight of atoms. Exception – fluorine, because of extremely low polarizability. Perfluorinated compounds (all hydrogens replaced by fluorines) participate very weakly in intermolecular attractions, which generate useful practical properties (the “no stick” cookware based on Teflon – a perfluorinated polymer).

B. Solubility in water – alcohols tend to dissolve much better, because of Hbond formation. Alkyl halides are insoluble.

C. Density – monofluorides and chlorides are less dense than water, but di- and polychlorides are denser.

7. Preparation of Alkyl Halides from Alcohols – one of the most popular methods is the reaction of alcohol with hydrohalic acid. This is a typical SUBSTITUTION process, which depends on the strength of the hydrohalic acid and so the order of reactivity is  $\text{HF} \ll \text{HCl} < \text{HBr} < \text{HI}$ . The most typical cases are HCl and HBr. As it turns out, the reactivity of the alcohols varies too – highest for tertiary, lowest for primary and methyl. HBr can be generated *in situ* (i.e. in the reaction mixture) by using NaBr and  $\text{H}_2\text{SO}_4$  as starting materials instead.

8. Mechanism of the reaction of alcohol with hydrohalic acid.

A. Some definitions:

- a. Mechanism – the complete, step-by-step description of the conversion of reactants to products.
- b. *Concerted* reaction and a stepwise process.
- c. Elementary step – a chemical transformation which involves a single transition state (TS).
- d. Molecularity of an elementary step – the number of species (molecules, ions, etc.) that participate in this step. One distinguishes *monomolecular* (or *unimolecular*), *bimolecular*, *termolecular* steps.

B. Reaction of *t*-butanol with HCl. Potential Energy Diagram.

The substitution of OH-group with a halogen is a stepwise process, i.e. it consists of more than one elementary step.

- a. Protonation of the alcohol – because of the lone pairs at the O-atom of the OH group, alcohols are *Brønsted* bases. Thus upon introduction of a hydrogen halide, they are immediately protonated. This is the first elementary step, and it leads to the generation of an *intermediate* – alkyloxonium ion. The step is bimolecular.
- b. Potential energy diagrams for chemical reactions – they present the change in energy versus the so-called reaction coordinate (RC). A reaction coordinate could be more than one quantity. Often it is defined by the extent to which a particular bond is being broken or created.
- c. The Hammond Postulate – there isn't any direct way one could investigate the nature of a transition state (i.e. isolation, spectroscopic studies, etc.), because it is an absolutely unstable formation. Thus, it is the Hammond postulate that allows us to make certain conclusions about its nature since the postulate states: **ANY TWO RELATED (I.E. NEIGHBORING) SPECIES ON THE POTENTIAL ENERGY SURFACE (DIAGRAM) THAT ARE CLOSE (SIMILAR) IN ENERGY ARE ALSO CLOSE (SIMILAR) IN STRUCTURE**

- d. In the particular case of protonation of *tert*-butanol, the step is exothermic and so the TS is closer in energy to the reactants, i.e. structurally it will resemble more the starting alcohol, with only a partial transfer of the H to the O atom. We call this kind of TS an “early” (or “reactant-like”) TS. If it resembled more the product(s), it would be called a “late” (or “product-like”) TS.
- e. The second step is the heterolytic cleavage of the C – O bond of *t*-butyloxonium ion, to produce a *t*-butyl cation, which is a carbocation. This step has much higher activation energy and produces an unstable intermediate. Thus the TS is considerably closer in energy to the intermediate (carbocation) and therefore must resemble it in structure. The step is unimolecular.
- f. The final step is a very fast association of the negative and positively charged species – the carbocation (a Lewis acid) and the chloride anion (a Lewis base). Or more properly – an attack of the nucleophile on the electrophile. The process has very small energy barrier and results in the final species – *t*-butyl chloride. The reaction is exothermic.
- g. The entire potential energy diagram has three TS. The TS for the production of the carbocation is highest in energy. This step is said to be rate-determining. REMEMBER: The rate of a multistep process is identical with the rate of its rate-determining step! Since the rate-determining step of the above process is unimolecular, the entire substitution reaction is called Unimolecular Nucleophilic Substitution (S<sub>N</sub>1).

#### 9. Electronic Structure and Stability of Carbocations.

Carbocations are divided into primary, secondary and tertiary, depending on the degree of substitution at the positively charged carbon. They all have planar geometries at the positive center, since it is sp<sup>2</sup>-hybridized. Stabilities increase in the order methyl < primary < secondary < tertiary. Two reasons for this: 1) The inductive effect of the alkyl groups and 2) The hyperconjugation effect of the alkyl groups. In fact, methyl cation, being exceptionally unstable, has NEVER been detected as an intermediate in S<sub>N</sub>1 reactions. Same with primary carbocations.

10. Effect of the Alcohol on Reaction Rate – since rate is determined by the value of activation energy (i.e. the energy barrier) it is then reasonable to recognize that higher in energy TS would mean slower reaction. But the TS of the rate-determining step of S<sub>N</sub>1 reactions are product-like, i.e. resembling the carbocations. We can therefore conclude that ANY FACTOR that affects the stability of the carbocation would affect in a similar way the stability of the TS. Hence it would be expected that the TS stability (and energy) would vary in the same fashion as the stability of the carbocations. In other words, MORE STABLE SPECIES ARE BOTH LOWER IN ENERGY AND FASTER TO OBTAIN!! The rate of the reaction would be expected to be highest for methyl alcohol, followed by primary alcohols, then secondary and fastest for tertiary.
11. Reactions of Primary Alcohols with HX and the S<sub>N</sub>2 Mechanism – the S<sub>N</sub>1 mechanism is not possible for methyl or primary alcohols, due to the very high energy (low stability) of methyl and primary carbocations. But there is an alternative way for the reaction to occur, albeit slowly: The protonated alcohol (i.e. the alkyloxonium cation) reacts in a concerted fashion with the bromide anion, without going through the stage of carbocation. Since in this case the rate-determining step is bimolecular (alkyloxonium ion + bromide anion), the entire substitution process is named S<sub>N</sub>2 – Bimolecular Nucleophilic Substitution.
12. Other Methods for Converting Alcohols to Alkyl Halides – the most popular reagents are thionyl chloride (SOCl<sub>2</sub>) and phosphorus tribromide (PBr<sub>3</sub>), for the conversion of primary alcohols to chlorides and bromides respectively
13. Preparation of Alkyl Halides by Halogenation of Alkanes – chlorination and bromination are most popular. Halogenation of alkanes follows a completely different, nonpolar mechanism. It involves the formation of electron-deficient, but neutral species – free radicals.
14. Electronic Structure and Stability of Free Radicals – carbon has incomplete octet, but charge is 0. A free radical has an odd electron, residing in the p-orbital (if sp<sup>2</sup> hybridization is valid, which is true in most cases!). Because of that it is a very

reactive species and another example of an intermediate. Divided, like carbocations, into primary, secondary and tertiary. Stability in the same order.

15. Bond Dissociation Energies (BDE) and the rate of generation of free radicals – the BDE is the enthalpy difference between the alkane and the free radical derived from it. The smaller the BDE, the more stable the radical. Tabulated results are in agreement with the earlier postulated order of stability of radicals. It takes the least amount of energy to produce a tertiary radical (and the greatest amount to make a methyl radical).
16. Mechanism of methane chlorination – it occurs via multistep, free-radical mechanism. The reaction requires an initiation step (to generate free radicals), after which it takes place as a chain-reaction.
17. Halogenation of higher alkanes.
  - A. Chlorination – chlorination of ethane produces a single compound, ethyl chloride. The outcome is unambiguous every time when a compound has only one type of hydrogens. But if there are several types, then several products would be expected. As it turns out, the outcome is not statistical, i.e. the amounts of products are not determined by the number of available sites for substitution. Rather, it depends on the RELATIVE REACTIVITY of these sites, which are in the order primary < secondary < tertiary. In the case of chlorination tertiary sites are about 5 times more reactive than primary. Overall, this is rather poor selectivity and mixtures of products result.
  - B. Bromination – bromine is less reactive than chlorine, but more selective. The difference in reactivity between tertiary and primary hydrogens in this case is more than 1500 times. Thus, reactions of bromination occur almost exclusively at the tertiary sites and tertiary bromides are obtained.