Aromatic Electrophilic Substitution reaction.

Continuation — Since in all the cases a large excess of nitrating agent is used, the reaction is of zero order with respect to the nitronium ion. The reaction is found to be of zero order, first order or fractional order depending on the nature of the substrate.

The zero order or pseudo-zero order reaction is followed by substrates which are more reactive than benzene. In these cases the reversible formation of the nitronium ion step is slower than the electrophilic ~~atta~~ attack step. Thus the rate-determining step is the reversible nitronium ion formation step: toluene, xylene follow this path way.

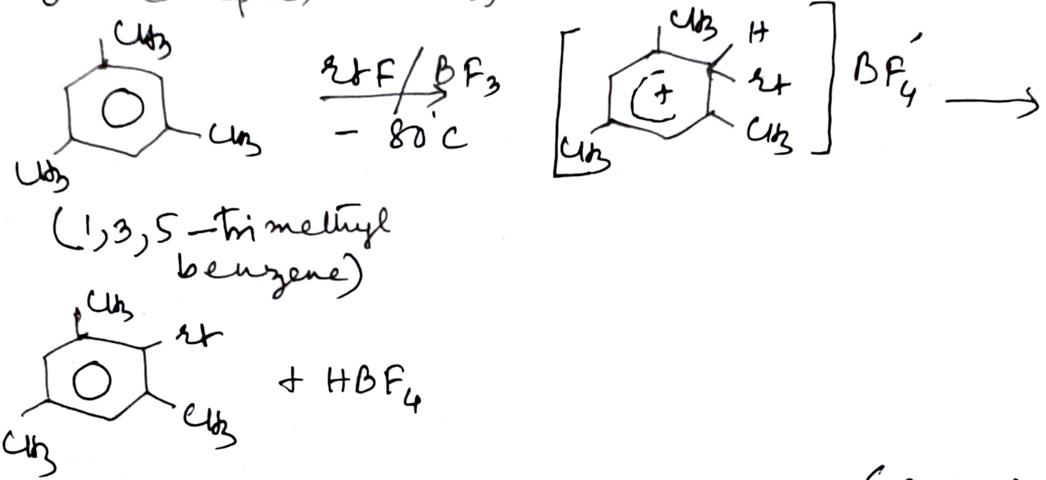
When the substrates are less reactive than benzene the nitronium ion formation step is found to be faster than the electrophilic attack step and as a consequence the reaction shows the first order kinetics with respect to the substrate. Thus in these cases the reaction is said to be the 1st order or the pseudo-1st order.

The rate = k [Substrate]. Ethyl benzoate, nitrobenzene follow the 1st order kinetics.

When the substrate is of intermediate reactivity, a non-integral order is followed by the reactions. It is between 0 to 1. An example of this kind is the nitration of chlorobenzene. The concentration of the reagent is also responsible for the non-integral order of the reaction.

Evidences in favour of ArS_E^2 mechanism.

a) Detection and isolation of σ– complexes: A large number of σ– complexes as intermediates in ArS_E2 reactions have been detected by NMR spectroscopic studies. Some of them also have been isolated as σ– complex salts.



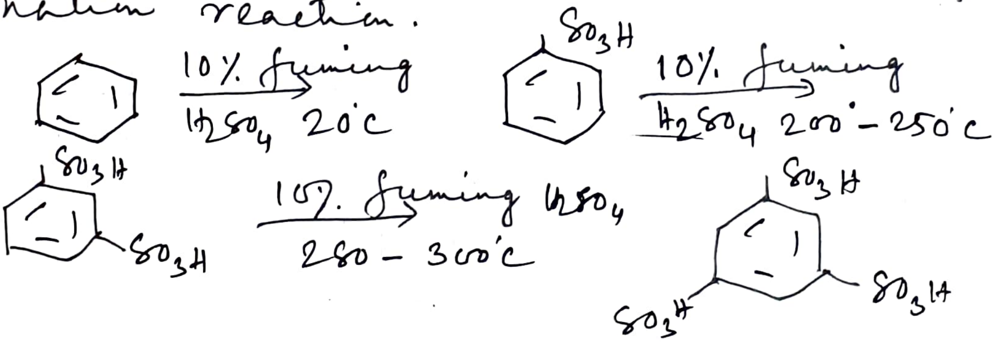
(1,3,5-trimethyl benzene)

b) Primary kinetic isotope effect (PKIE): Displacement of a H (or D) atom of C_6H_6 (or C_6D_6) by a nitronium ion (NO_2^+ ion) is an $ArSE2$ reaction which is irreversible in nature. It has been found that, the rate of formation of $C_6H_5NO_2$ from C_6H_6 is almost equal to the rate of formation of $C_6D_5NO_2$ from C_6D_6 under the same reaction conditions. It implies that the rate of breaking of C–H bond is equivalent to the rate of breaking of C–D bond. This proves that the elimination of H^+ as an electrofuge is a fast step and the formation of σ– complex (Step-1) is the rate determining step.

Rate of aromatic S_E^2 reaction: The rate of ArS_E^2 reaction is enhanced by the presence of electron donating substituents (with +I and +R effect and hyperconjugative effect). Strong electrophiles also increase

-ase the rate. On the other hand, substituents with electron with drawing effect (−I, −R effects) and weak electrophiles decrease the reaction rates. Substituents with +I and +R effects increase the electron density on the aromatic ring, thereby facilitating the ArS_E^2 reaction and are known activating groups. The substituents with −I/−R effects will draw electron density from the aromatic ring and thereby the rate of the reaction decreases. The substituents are known as deactivating groups.

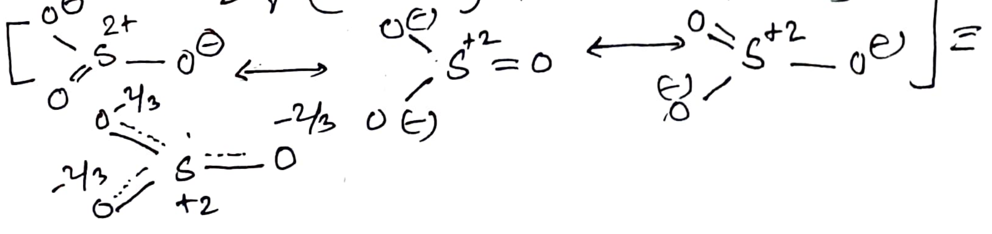
Aromatic sulphonation reaction: The process of introducing a −SO_3H group into an aromatic nucleus by the action of concentrated H_2SO_4 or fuming H_2SO_4 [oleum ($H_2S_2O_7$ − SO_3 in H_2SO_4] or SO_3 in organic solvent or chlorosulphonic acid in carbon tetrachloride is known as aromatic sulphonation reaction.

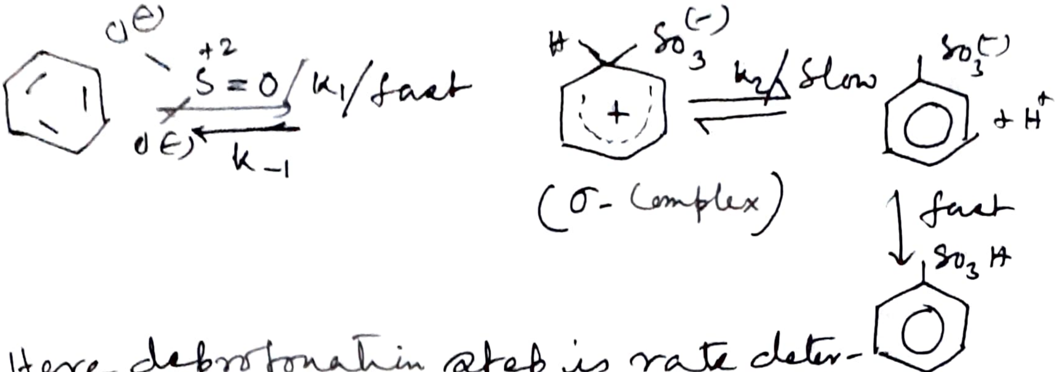


Mechanism of sulphonation reaction: When the sulphonating reagent is concentrated H_2SO_4 or fuming H_2SO_4 or SO_3 in organic solvent, the electrophile is SO_3

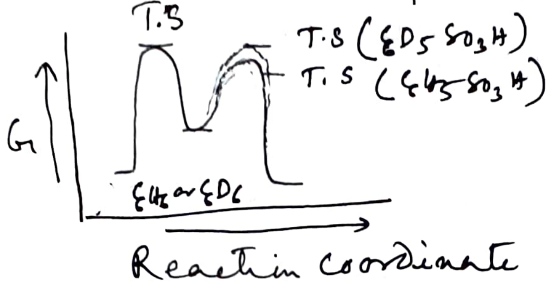
$$2H_2SO_4 \rightleftharpoons SO_3 + HSO_4^- + H_3O^+$$

$$H_2S_2O_7\ (\text{oleum}) \rightleftharpoons H_2SO_4 + SO_3$$





Here deprotonation step is rate determining step, not the formation of σ-complex which is observed in irreversible ArS_E2 reaction. This is proved by PKIE effect.



Energy profile of aromatic sulphonation reaction in C_6H_6 and C_6D_6

Evidences for the SO_3 as attacking electrophile

1. Rate of sulphonation is higher with SO_3 compared to H_2SO_4. The reaction rate is proportional to the concentration of SO_3.

2. Deprotonation step shows PKIE. This indicates that C–H bond breaking is involved in rate determining step, i.e. $K_{-1} > k_2$ and the heights of two transition states being almost equal, and the reaction becomes reversible.

Aromatic chlorination and Bromination:–

Chlorination and bromination of aromatic rings may be carried out at ordinary temp by allowing the compound to react with molecular chlorine or bromine in the presence of Fe or a Lewis acid e.g. $AlCl_3$, $AlBr_3$, $SbCl_5$, $SbBr_5$ etc. But in these cases either a halide ion or an acid is to be added to speed up the reaction.

Activated compounds react with molecular chlorine and bromine even in the absence of a Lewis acid. e.g. phenols, amines etc.

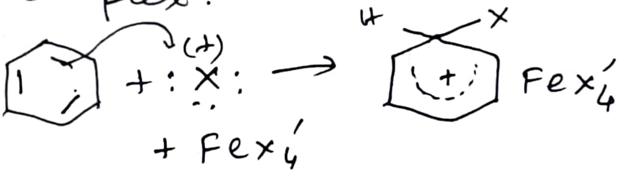
Depending on the nature of halogenating agents, three types of mechanism are to be discussed.

i) Mechanism of halogenation with iron and halogen: a) According to some authors Chloronium or bromonium ion is the attacking electrophile. The halonium ions are supposed to form by the following way:

$$2Fe + 3X_2 \rightarrow 2FeX_3 \; ; \; :\ddot{X}-\ddot{X}: + FeX_3 \rightarrow$$

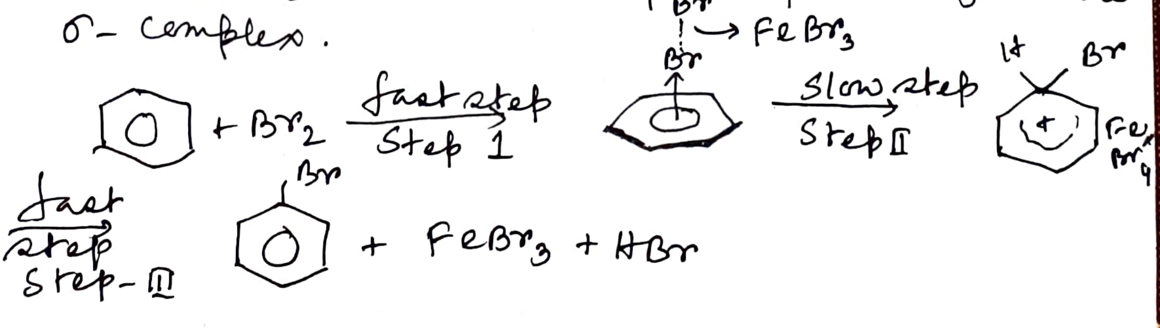
$$:\ddot{X}-\ddot{X}^{(+)}—\overset{(-)}{Fe}X_3 \rightleftharpoons X^{(+)} + FeX_4'$$

Step 1. The halogenonium ion then attacks a ring carbon as an electrophile and forms a σ- complex.



Step II: The σ- complex then gives up a proton to the Lewis base, FeX4', and gets aromatized

b) According to some authors, the molecular halogen forms a π- complex with the aromatic compound, the Lewis acid then pulls the X⁻ part of the complex and thus helps to form the σ- complex; ultimately the conjugate base of the Lewis acid takes up the proton from the σ- complex.



The rate = k [Substrate] $[X_2]$ [Lewis acid]

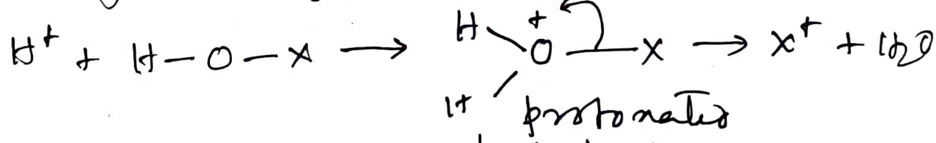
This rate order is often followed by the halogenation processes and supports the π-complex mechanism (b). Therefore, step II of (b) pathway is the rate determining step. NO primary kinetic isotope effect has yet been observed with chlorination (and rarely with bromination). This suggests that C—H bond-breaking step is not the rate determining step.

ii) Mechanism of halogenation with hypohalous acid and halide ion: When the reagent is hypohalous acid and corresponding halide ion, the attacking species is supposed to be the molecular halogen which is formed as shown below:

$$2H^{+} \quad O^{-}—X + X^{-} \longrightarrow H_2O + X_2$$

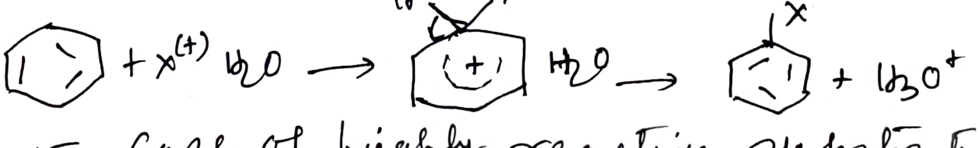
This molecular halogen through π-complex and σ-complex formation with the aromatic ring produces the haloarenes.

iii) Mechanism of halogenation with hypohalous acid and a strong acid: In this case the attacking electrophile is either protonated hypohalous acid or the halonium ion which is formed by the following pathway.



$$H^{+} + H—O—X \longrightarrow H_2\overset{+}{O}—X \longrightarrow X^{+} + H_2O$$

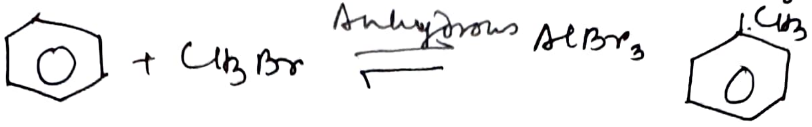
protonated hypohalous acid

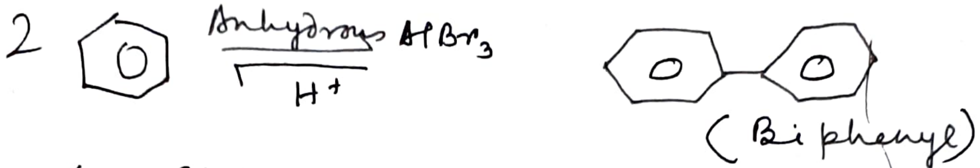


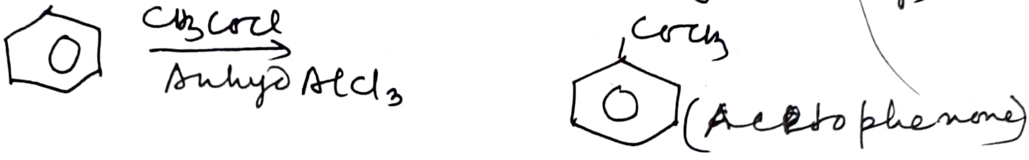
In the case of highly reactive substrate such as phenol, anisole, aniline, etc. the reaction become very nearly of zero order in the substrate and 2nd order overall.

The rate = k [H-OX][H^+][Substrate]

The Friedel craft reaction – Introduction of an alkyl or an aryl or acyl group into an aromatic nucleus in the presence of a Lewis acid or a protonic acid as catalyst is known as Friedel-Crafts reaction







Depending on the nature of the alkyl halide Friedel craft alkylation, reaction (an aromatic SE2 reaction) follows two different mechanistic courses.

i) when the alkyl halide is methyl or 1°, the reaction occurs through the steps as follows:

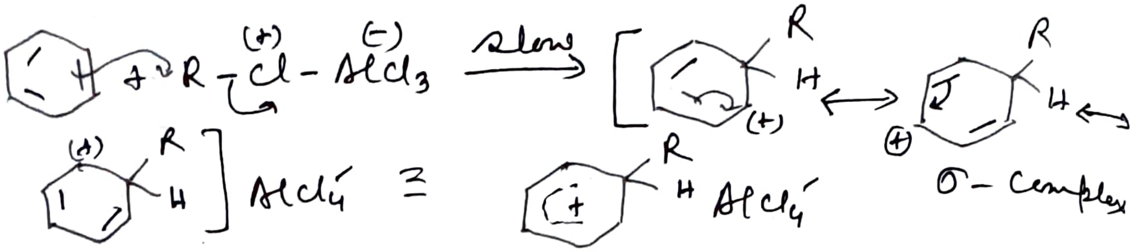
Step I: The alkyl halide (e.g. R–Cl) forms a complex with the Lewis acid $AlCl_3$

$$R-\ddot{C}l: + AlCl_3 \rightleftharpoons R-\overset{(+)}{Cl}-\overset{(-)}{Al}Cl_3$$

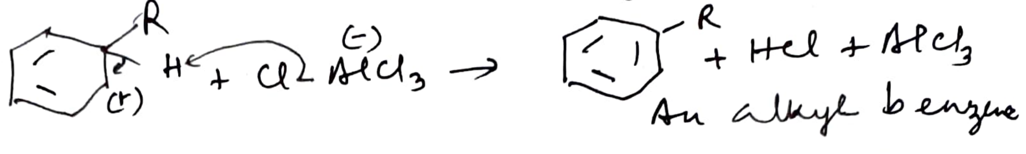
Alkyl chloride
-aluminium chloride
complex

The C–Cl bond of the complex is nearly broken and the carbon atom has a considerable positive charge. The complex does not dissociate to form ions ($R^+ + AlCl_4^-$) because the carbocations if produced as such will be very unstable (methyl or 1° carbocation)

Step II: The complex as a whole attacks the benzene ring through the partially positive carbon atom to form a σ-complex. It is the rate determining (slow) step of the reaction

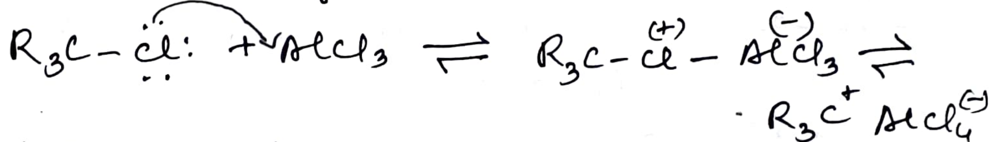


Step II The σ– complex loses a proton and regenerates an aromatic system

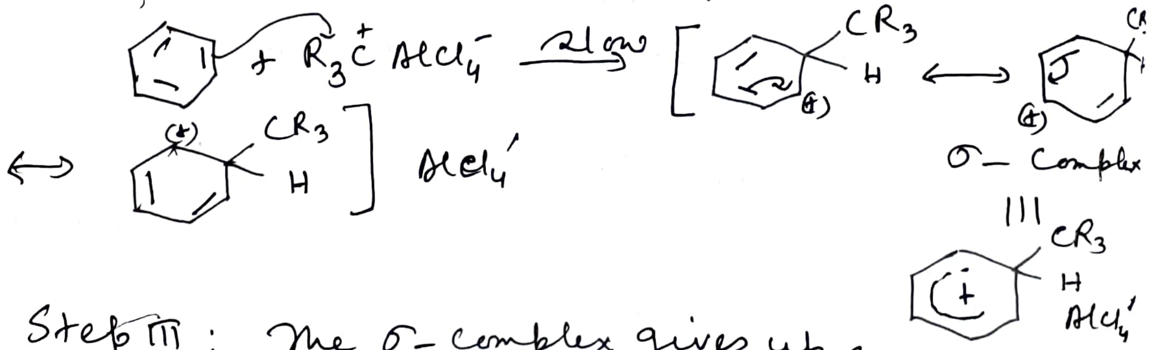


ii) when 2° or 3° alkyl halide is involved the reaction occurs through the following step

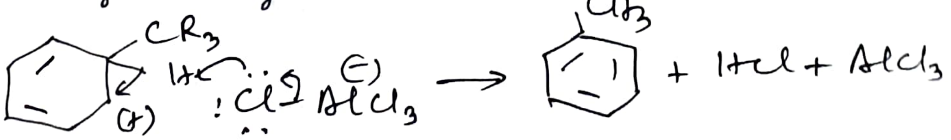
Step I : The tertiary alcohol reacts with $AlCl_3$ to form a very stable 3° carbocation



Step II The electrophile $R_3C^{(+)}$ attacks the benzene ring to form a σ– complex



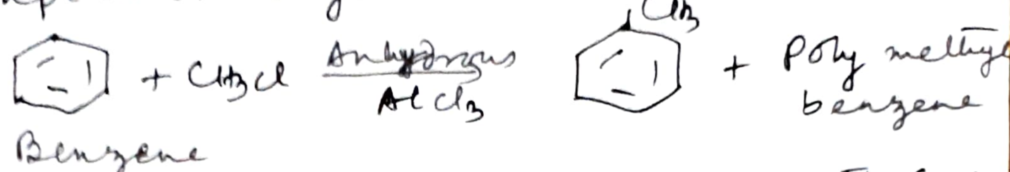
Step III : The σ– complex gives up a proton to $AlCl_4^-$ and gets aromatised to form an alkyl benzene.



Only a catalytic amount of $AlCl_3$ is required in this reaction because the catalyst used in Step I is regenerated in step III and the regenerated catalyst works again.

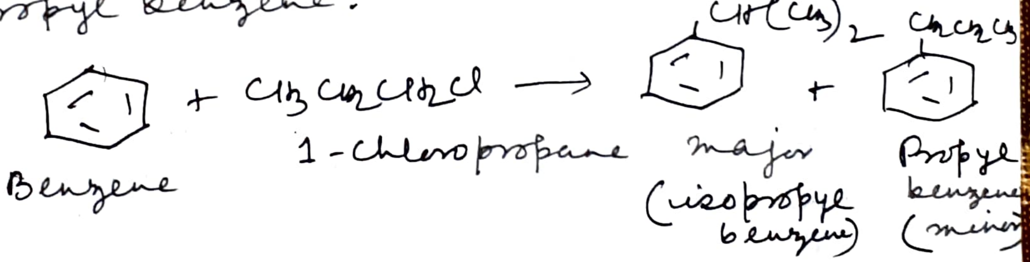
* Limitation of Friedel craft Reaction:-
It is difficult to stop the reaction at

the mono alkylation stage because introduction of one alkyl group tends to active the ring towards a second substitution. The result is the formation of poly alkylated compounds along with the desired mono alkylated compound. e.g.

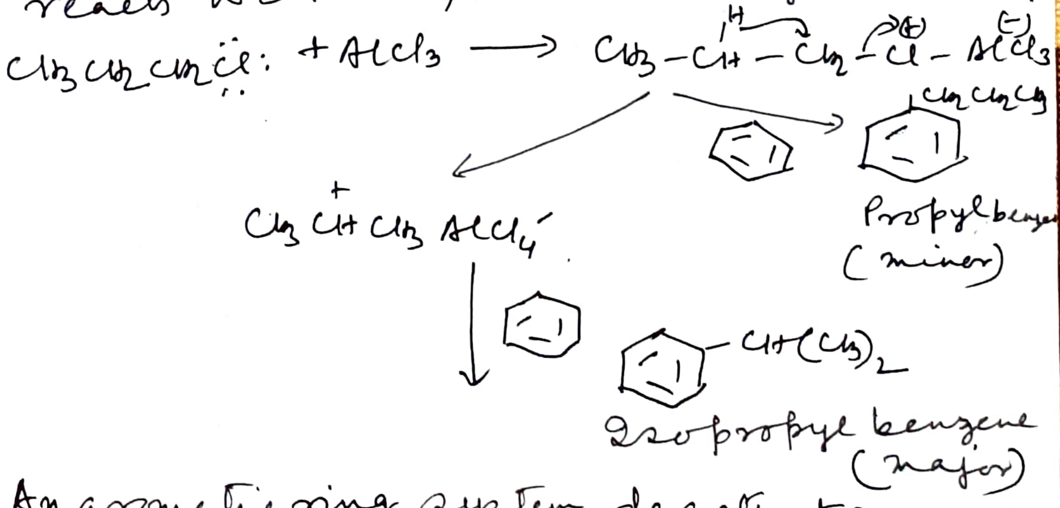


Although use of an excess of the aromatic compound favours mono alkylation, the synthetic utility is reduced.

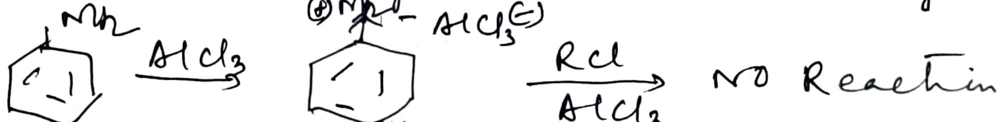
ii) The rearrangement of a developing less stable carbocation to a more stable one often results in predominant formation of an undesired rearranged product. e.g. 1-Chloropropane with benzene in the presence of $AlCl_3$ yields mainly iso propyl benzene.

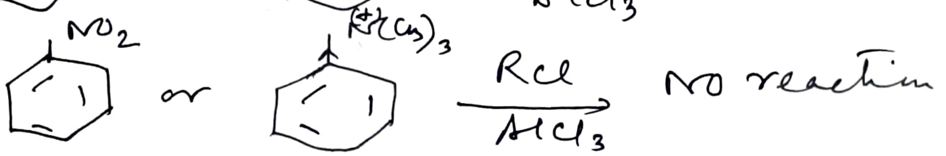


During ionisation of the Lewis acid complex the developing 1° carbocation rearranges to a more stable 2° carbocation which reacts with to yield the major product.



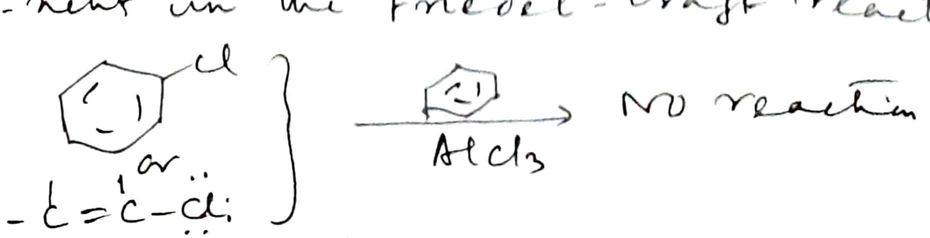
iii) An aromatic ring system deactivated more than that of halo benzenes does not undergo the Friedel-Crafts reaction. This is because the carbocation involved in this reaction is a relatively weak electrophile and it is unable to attack a much deactivated ring. The reaction does not occur when powerful electron-withdrawing groups such as $-NO_2$ and $-\overset{+}{N}(CH_3)_3$ are present on the ring. Also the rings containing the amine groups, $-NH_2$, $-NHR$ and $-NR_2$ do not undergo this reaction because these groups become converted into powerful electron withdrawing groups by co-ordinating with the Lewis acid used to catalyse the reaction. e.g.





iv) Aryl halides cannot replace alkyl halides in this reaction. Unlike alkyl halides, the carbon bearing halogen in aryl halides is sp^2 hybridised and also there operates electron delocalisation between the halogen and the ring; these makes the C–X bond shorter and stronger. The Lewis acid is unable to ionize this stronger C–X bond and so the reaction does not take place.

Due to same reasons vinylic halides cannot be used as the halide component in the Friedel-Craft reaction.



A vinyl chloride