COMPARATIVE STUDY OF AROMATIC ELECTROPHILIC SUBSTITUTION REACTION AT THE META AND ORTHO-POSITION IN TOLUENE

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Abstract- *The approach of this theoretical work is to study the step by step mechanistic pathway of electrophilic substitution reaction in substituted benzene and evaluating energy of each species involved in the mechanism. Toluene was taken as substituted benzene, nitronium ion was taken as an electrophile while hydrogen ion (H^+) act as the leaving group. The Methyl group present in the ring is an electron donating group. Therefore, its effect on electrophilic substitution of hydrogen from the ring system was taken into consideration. Quantum mechanical based computational calculation was employed for determining energy of molecular/ionic structures involved in the mechanism, where activation or deactivation of the ring by methyl substituent and its directing behaviour to the meta or ortho position for electrophilic substitution were also included for a part of the study. The study is based upon the energy calculation of different structures in the mechanistic pathway and calculation of activation energy for 1, 2-shift in meta and ortho-positions.*

Keywords: **1,2-shift, meta and ortho-positions, electrophilic substitution, mechanistic pathway, toluene, nitronium ion, activation energy**

1. INTRODUCTION:

Since aromatic compound has electrons delocalizing in the ring system, it can act as a nucleophile where electrophile can attack with its positive center or vacant orbital. There are four different reactive positions in a mono-substituted benzene. The ring carbon atom bearing the substituent is called ipso, the next ring carbon is ortho, the third position is meta and fourth position is Para.

Substituents are generally divided into two classes based on their electron donating and electron withdrawing properties. Deactivating substituents destabilize the intermediate cation by withdrawing electron density from the aromatic ring and thus decrease the reaction rate of reaction. On the other hand, activating groups stabilize the cationic intermediate formed during the substitution by donating electrons into the ring system, by either inductive effect or resonance effects.

In the first step of electrophilic substitution reaction, nucleophile attacks the aromatic ring at any one of different positions. This leads to the formation of a positively-charged cyclohexadienyl cation, also known as an arenium ion. This carbocation is unstable, owing both to the positive charge on the molecule and to the temporary loss of aromaticity. However, the cyclohexadienyl cation is partially stabilized by resonance, which allows the positive charge to be distributed over three carbon atoms. In the second stage of the reaction, a proton leaves the ring and the shared electrons return to the $\pi\pi$ system, restoring aromaticity.

In electrophilic substitution reaction, hybridisation change is also observed at the carbon where new sigma-bond is formed between the incoming electrophile and the carbon which is being attacked. The orbital with sp^2 before the attack get changed to sp^3 after a new bond has been formed. After deprotonation sigma bond between carbon and hydrogen is broken and the sigma electrons get changed to pi-electron thus carbon restore its sp^2 hybridised orbital.

2. METHODOLOGY:

Calculation of the gradient-corrected electron density function, geometries, energies and frequencies of different structure obtained in the mechanisms was done by using the gradient-corrected hybrid B3LYP basis function with 6-31G* standard split valence basis set of the Density Functional Theory method of Gaussian 98 revision A.11.2 package. The transition state for the migration of nitronium ion from meta-C to ortho-C were located by using the standard saddle principle of the Gaussian 98 package, invoking a reverse search strategy with interpolation between the equilibrium geometries of the reactants and products to arrive at the transition state. Once located, the transition state was verified. Energy- minimized heats of formation were calculated for each of the molecular species involved in the mechanism and used as the basis for calculating the energy profile for the reaction pathways in each case.

The study of the reaction was based upon the energy involved due to steric interaction, angle strain, geometries, frequency, etc. Once the energy for each intermediate was calculated, the feasibility of the reaction can be predicted. All the structures were calculated in the semi-empirical AM1 method and the Density Functional Theory (DFT) B3LYP/6-31g* levels of calculations and Hartree energies were obtained for all the cases. The Hartree energies were then all converted to the corresponding Kcal/mole where the first structures for all the cases were taken as zero and the rest of the structures were calculate with respect to the first structure for all the mechanisms studied. All values taken into consideration for our study here are taken from the DFT calculations.

3. RESULT AND DISCUSSION:

Mechanism A: This mechanism involves the attack of nitronium ion by the ?-electron in the benzene ring at the meta-position as given in figure 1. Subsequently structure **II** loses its aromaticity, which is again regained by deprotonation in structure **III.** This deprotonation process being facilitated by the electron-deficient carbocation center in the ring. Structure **II** gaves rise to two resonating structures with different environments.

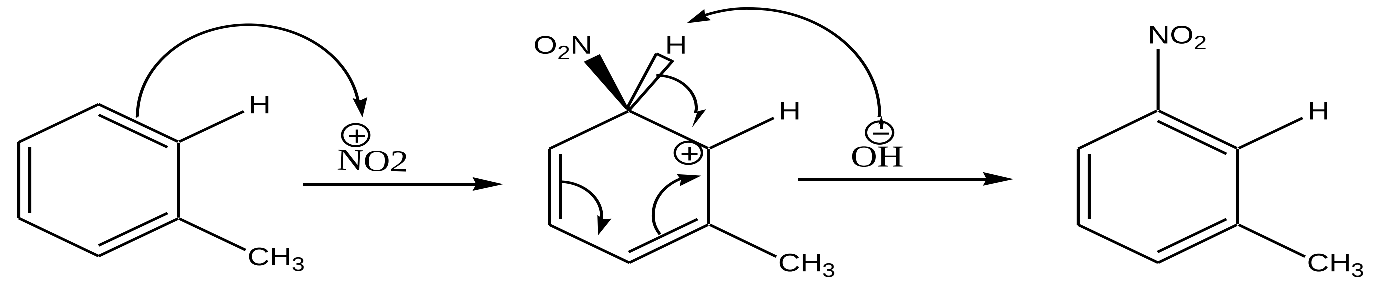
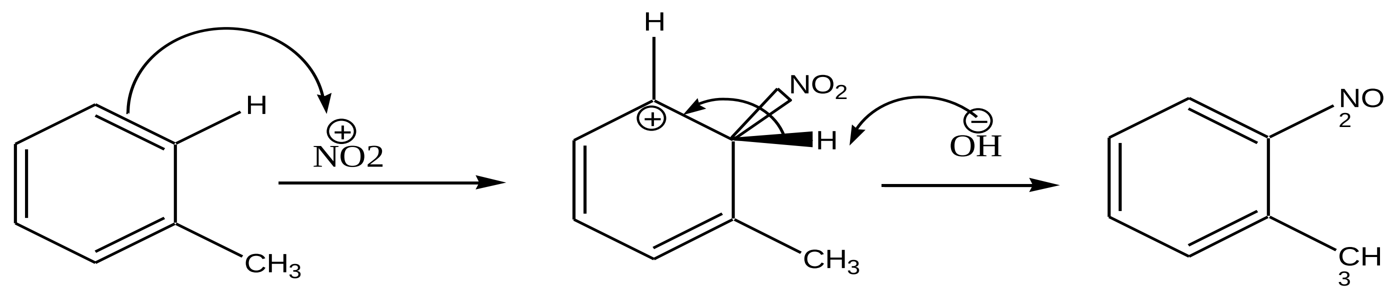


Figure -1*: Mechanism **A** showing the nitration and the deprotonation steps*

TABLE-I: *Energy calculated for each structure in **mechanism A** , total energy in hartrees and the relative energy in Kcal/mol.*

Structure	AM1	AM1 (RE)	AM1 OPT	AM1 OPT(RE)	B3LYP	B3LYP (RE)
A-I	32	0	51	0	298227	0
A-II	325	293	224	173	298725	498
A-III	99	67	78	27	298622	395

Mechanism B: The second mechanism begins with the attack at the ortho position to the substituent, rearrangement (resonance) in structure **II** is followed by deprotonation, then the benzene ring restores its aromaticity. In this mechanism, Structure **II** may give rise to three resonating structures with different environments.



I II III

Figure-2*. Mechanism **B** showing the nitration and the deprotonation steps.*

TABLE-II*. Energy calculated for each structure of **mechanism B**, total energy in hartrees and the relative energy in Kcal/mol.*

Structure	AM1	AM1 (RE)	AM1 OPT	AM1 OPT(RE)	B3LYP	B3LYP (RE)
B-I	32	0	51	0	298227	0
B-II	312	280	221	170	298719	492
B-III	98	66	77	26	298619	392

Mechanism C: This mechanism involves the attack at the meta-position to the substituent followed by 1,2- shift of the attacking electrophile (NO_2^+). The direction of the migration is from the meta-position to the ortho-position as shown in figure-3. Deprotonation finally gives back the aromaticity to the benzene ring. The migrating abilities of the incoming nitro group is very helpful for understanding the most probable mechanistic pathways. Mechanism **C** is nothing but the inclusion of mechanism **A** and **B** as well as transition state as a single mechanistic pathway.

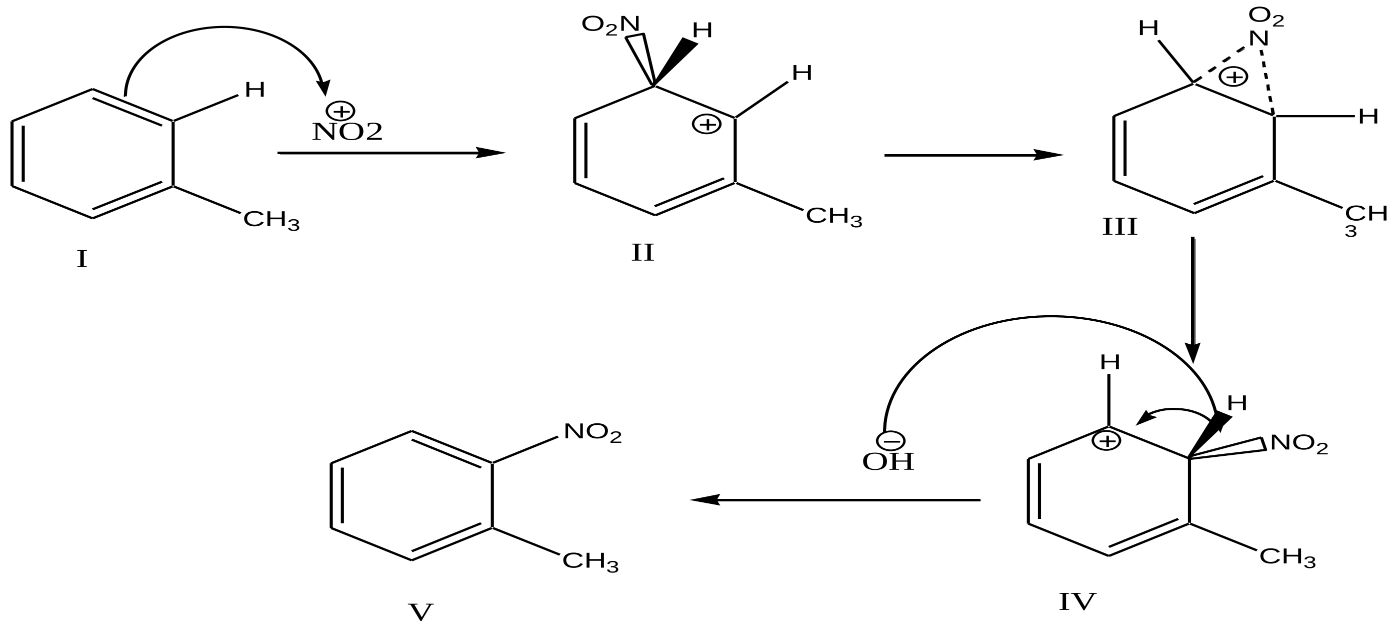


Figure-3: *Mechanism **C** showing the nitration, 1,2-shift via a transition state and the deprotonation step.*

TABLE-III: *Energy calculated for each structure of **mechanism C**, total energy in hartrees and the relative energy in Kcal/mol.*

Structure	AM1	AMI(RE)	AM1 OPT	AM1 OPT (RE)	B3LYP	B3LYP(RE)	Ea-1 (Kcal/m) II→III	Ea-2 (Kcal/m) IV→III
C-I	32	0	51	0	298227	0		
C-II	325	293	224	173	298725	498	9	15
C-III			279	228	298734	507		
C-IV	312	280	221	170	298719	492		
C-V	98	66	77	26	298619	392		

Ea-1 gives the energy required for Structure –II(C-II) to climb up the peak of Transition state (C-III). The quantity of this energy determines the ease with which Structure-II(C-II) can be converted into structure-IV(C-IV). More the value of this energy more will be the energy required to get converted into structure-IV(C-IV). In the same way **Ea-2** describes the feasibility of conversion of structure-IV(C-IV) to structure-II(C-II).

As shown in the table, since structure-II(C-II) has energy higher than Structure-IV(C-IV), Meta-substitution at the intermediate is supposed to increase the energy of the ring system to a greater extent than that of ortho-substitution. Comparing structure A-III and B-III, energy calculated by different methods revealed that A-III has higher energy than B-III in all calculations. This is an indication of the more stability of molecule where the substitution is done at the ortho-position than at the meta-position when the substituent is an electron donating group.

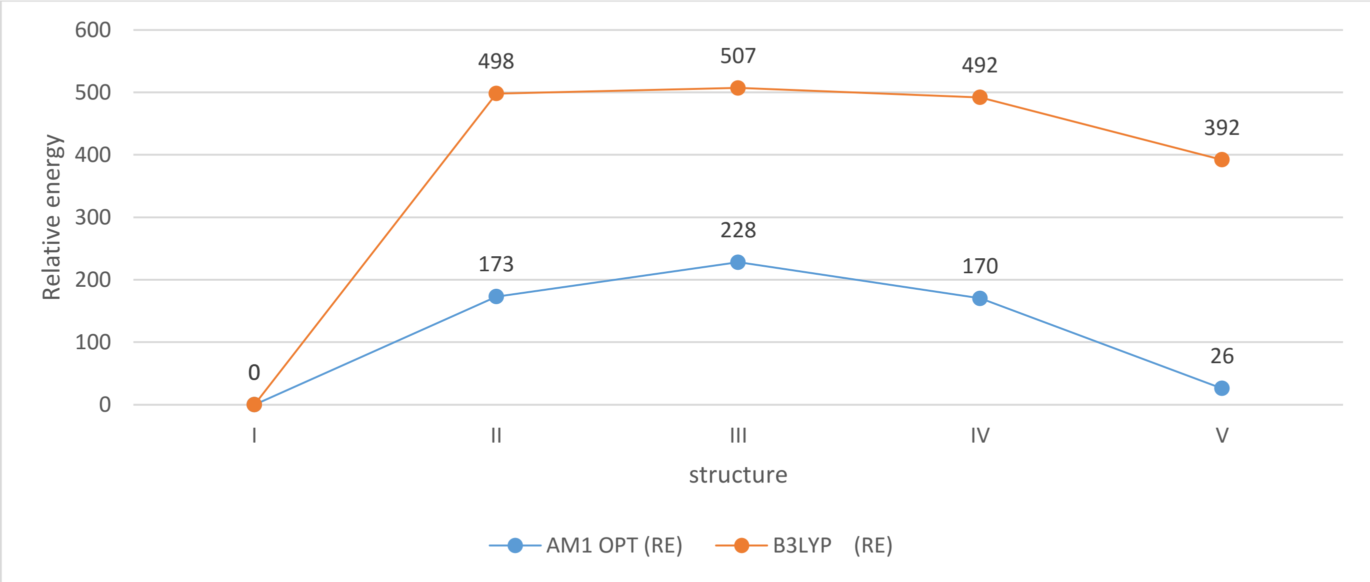


Figure-4: *Graph showing relative energies of different structures (AM1 and B3LYP*)

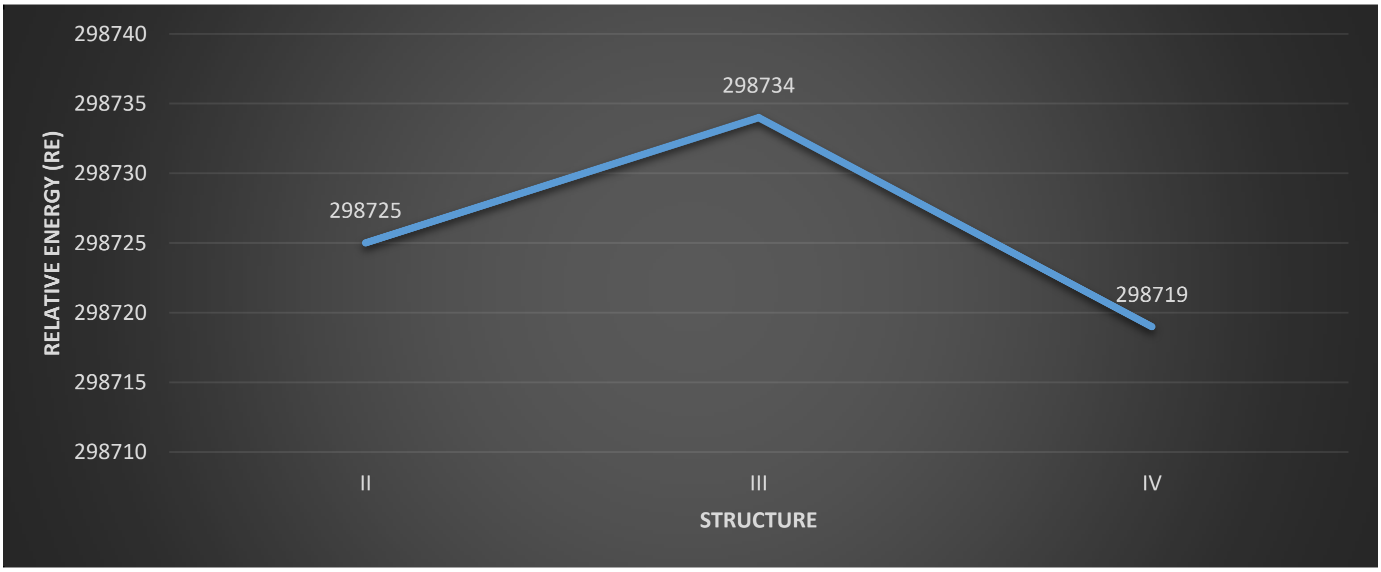


Figure-5: Graph showing the energy of structure II, III and IV. The differences in energy of C-II and C-III is Ea-1 and the differences in energy of C-IV and C-III is Ea-2.

Comparison of ortho and meta-position:

For each mechanism, structure I is toluene therefore, the energy calculated was same for all mechanistic pathways. **In mechanism C** all the structures in mechanism **A** and **B** as well as structure **C-II** (Transition state) were included. In all calculations structure **B-II** or **C-IV** has lower energy than structure **A-II** or **C-II**, it is attributed to the localization of positive center at the carbon bonded to the electron donating methyl group, the positive charge at the carbon can be partially stabilized by electron donating methyl group and more resonating structures as well as more number of ways of positive charge distribution in the ring is possible. In addition to this, methyl group activates the benzene ring by pushing electron cloud toward the ring thus making the ring more facile for the attack of electrophilic reagent this effect is more pronounced at the meta-position.

Structure **A-III** has more energy compared to **B-III** the reason seems to lie upon the otho-directing property of methyl group by reason of its electron donating effect. If we compare the activation energy of **C-II** and **C-IV** for climbing up transition state **C-III**, Activation energy of **C-II (Ea-1)** is lesser than **C-III (Ea-2),** this implies that it is more difficult to transform **C-IV** to **C-II** through transition state than from **C-II** to **C-IV**.ie. less energy will be required for transition from **C-**

II to **C-IV**. On the other hand 1, 2- shift from meta to ortho is easier than the reversed 1,2-shift if the substituent already present in the ring is an electron donating group.

4. CONCLUSION:

From the theoretical study of aromatic electrophilic substitution reaction in the gaseous phase, the energy calculated for different structures in the mechanism and activation energy for 1, 2-shift in ortho-meta transition reveals that ortho-substitution is more easier than that of meta-substitution if the substituent already present in the ring is an electron donating group.

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