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Dft-based analytical evaluation of reaction pathways and stereochemical behavior

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Abstract: This paper involves an analytical analysis of reactions pathways and stereochemical behavior of some organic elimination reactions using Density Functional Theory (DFT). Mechanistic and energetic properties of ethyl chloride and 2(dimethylamino)ethyl chloride were studied based on B3LYP functional with 6-31++G(d,p) basis set. The optimization of geometry of reactants, transition states and products was conducted to gain insight into the change in structure throughout the reaction process. Energetic parameter like activation energy, enthalpy and Gibbs free energy were determined in order to determine the viability of various reaction paths. The findings suggest that the non-assisted elimination route is energetically more preferable over the anchimeric-assisted one. The changes in the distribution of electrons and bond order in the reaction were also determined by Natural Bond Orbital (NBO) analysis and Wiberg bond indices. These results allow obtaining a vivid idea of the reaction mechanism, changes in electronic structure, and stereochemical behavior by showing that DFT techniques are useful in the study of reaction kinetics and mechanistic pathways in organic chemistry.

Keywords: Density Functional Theory (DFT), Reaction Pathways, Stereochemistry

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INTRODUCTION

The Density Functional Theory (DFT) has become one of the most popular and effective methods of computations of chemical systems on the molecular and atomic level. It has since the last several decades become a necessary accessory of theoretical and computational chemistry as it provides a predictive accuracy that is at a reliable cost in terms of computational efficiency. In contrast to the classical quantum mechanical approaches which demand a heavy number of computational resources, DFT works with the electron density of a system as opposed to the many-electron wavefunction, making complex calculations much easier. This benefit enables the researcher to study large and complex chemical systems that otherwise would be hard to study with solely experimental techniques. DFT is an important tool in current chemical research to understand reactions mechanisms, predicting molecular structure and properties, as well as to analyze energetic aspects of chemical reactions. With the ongoing increase in computational power, DFT has gained more significance in terms of filling the gap between the theory of chemistry and the experimental data and, therefore, gaining a better understanding of the behavior of molecules and chemical reactions.

Reaction pathways are described as the series of intermediate states and transition states through which a chemical system goes through when reactants are transformed into products. The knowledge of these pathways is essential in the explanation of how chemical reactions take place and why some products are formed selectively as opposed to the rest. To every one of the reaction pathways there is a corresponding

potential energy surface which characterizes the energetic changes that the reacting molecules undergo through the reaction. According to traditional experimental methods, one can usually only obtain data on the starting reactants, and end products, but the intermediate species and transition states are not readily observed because they have short lifetimes, and they are often relatively unstable. In this regard, the DFT-based analytical techniques have become highly useful in the sense that they allow researchers to investigate the potential energy surface in theory. Computational modeling provides researchers with access to the location of the transition states, intermediates as well as the energy barriers of a chemical reaction. This theoretical insight aids in drawing up an extensive image of the reaction mechanism and enhances our knowledge of the manner in which molecular transformations occur.

Reaction kinetics is one of the most important topics in the study of reactions and it is concerned with the speed of chemical reactions and the factors that determine these speeds. Reaction kinetics contributes key role in the issue of the efficiency with which a chemical process occurs and the optimization of the factors of reaction to give desired products. DFT calculations provide scientists with significant kinetic quantities of activation energy, transition state structures, and rate constants. The activation energy is the lowest energy that is needed by reactants to overcome the energy barrier to be able to form products. Researchers are able to determine the rate limiting step of a reaction mechanism through the analysis of transition state geometries and the energy barriers associated with the geometries. This type of information can be be of great value in forecasting the speed of a reaction in various temperature or pressure conditions. In addition, reaction kinetics investigations performed by computational chemistry aid chemists in creating more efficient synthetic pathways and improve the industrial chemistry processes in various applications including catalysis, environmental chemistry, materials science and pharmaceutical development.

Another important part of chemical reactions is stereochemistry, which is especially relevant to organic and biological systems in which the geometry of atom arrangement in the molecules is decisive in chemical reactions. Stereochemistry is concerned with the spatial arrangement of atoms and the effects of such arrangement on chemical reactivity, selectivity and formation of products. Though numerous chemical reactions can form a variety of stereoisomeric products, molecules that have the same molecular formula but differ in the spatial arrangement of its atoms. Such stereoisomers tend to have different physical, chemical and biological characteristics. As an illustration, one of two stereoisomers of a single compound can exhibit strikingly different biological behavior, with one stereoisomer becoming either a potent drug and the other a silent (or even toxic) one. Thus, the knowledge of and regulation over stereochemical results of chemical reactions are highly crucial in the development of selective and efficient synthetic reactions.

DFT-based analysis studies are useful to study the behavior of stereochemistry because they enable the researcher to study geometries, electronic distributions and orbital interactions of molecules in detail. Computational simulations allow one to determine the orientation of the molecules in a reaction, and the most probable stereochemical pathway that will take place. Using the optimized structures of reactants, intermediates, and transition states, scientists are able to identify the spatial arrangement that prefers the development of certain stereoisomers. The predictions have found application especially in asymmetric synthesis and drug design, in which it is essential to control the stereochemistry of a reaction to obtain desired biological properties. Moreover, DFT computations allow scientists to assess both steric and

electronic effects which determine stereochemical selectivity as such, to give a better insight into how chemical reactivity and product distribution are related to the structure of a molecule.

The next significant strength of DFT methods is that it can give detailed data regarding the electronic structure of the molecules engaged in reaction pathways. Electronic structure analysis is a study that determines the pattern of distribution of the electrons in a molecule and the way in which the electrons are involved in chemical bonding and reactivity. DFT provides the ability to compute electron density maps, molecular orbitals, charge distributions, and other electronic properties to observe how such properties affect the stability and reactivity of chemical species. This knowledge will aid in understanding why some bonds break or form in a reaction and how the electronic interactions aid in the stabilization of the transition states or intermediates. Further, other computational methods like Natural Bond Orbital (NBO) analysis and molecular orbital analysis give a greater understanding of the electron delocalization, the process of charge transfer, and orbital interactions that can control any chemical reaction. These e-clues play a vital role in describing the basic phenomena of chemical reactivity, as well as in forecasting the effects of changes in molecular structure that can change the results of reactions.

Moreover, the analytical evaluation performed with the help of DFT enables the researcher to compare a variety of possible reaction pathways and identify the most energetically favorable one. In most chemical reactions, a number of mechanisms can in principle occur, but only one or two can be dominant because of lower activation energies or more stable intermediates. DFT methods are used to determine the least amount of energy that will be needed to pass through a specific transition state or intermediates and compare the energies to find the pathway that is the most likely to take place. This would be of great use especially in catalyst design, optimization of reaction and planning of synthesis. Catalytic reactions Catalytic reactions for example, learning how catalysts reduce activation barriers and stabilize transition states can be used to create more effective and selective catalytic systems. Consequently, computational forecasts within the framework of DFT frequently inform experimental chemists to plan and enhance the reaction efficiency, as well as form more focused experiments.

To sum up, the DFT method has played a significant role in the analysis of reaction pathways and stereochemical reactions by offering highly important information on the processes of chemical reactions on a molecular scale. DFT offers detailed information on the reaction mechanisms, energy profiles, and stereochemical outcomes by combining the theoretical modeling and the basic chemical principles. Computational methods of investigating chemical systems are enabled by the ability to analyze molecular structure, electronic properties, and reaction kinetics and are often challenging to obtain experimentally. This is likely to have even greater importance in the development of modern chemistry with the ongoing evolution of computational techniques making use of DFT. These works can be used in addition to basic scientific knowledge as well as in the rational design of new reactions, catalysts and functional molecules to be applied in pharmaceuticals, materials science and industrial chemistry.

LITERATURE REVIEW

Sobhi, Chafia & Abdelmalek. (2016). With the use of the standard 6-31G(d) basis set and the B3LYP and ὐB97XD density functional theory techniques, the stereoselectivities and regioselectivities of the [3 + 2] cycloaddition (32CA) reaction between trans-β-nitrostyrene and 3-(benzylideneamino) oxindole (AY)

have been investigated. We have investigated and identified four reactive pathways linked to ortho and meta regioselective channels, as well as endo and exo stereoselective treatment modalities. The ὼB97XD functional is able to anticipate the experimentally observed meta regioselectivity, which supports the production of meta/endo cycloadduct as the primary isomer, in contrast to the B3LYP functional, which is unable to do so. By accounting for solvent effects, we can boost regioselectivity while dampening the stereoselectivity we saw in the experiments. The strong polar nature of this zwitterionic-type 32CA reaction may be explained by analyzing the Parr functions of the reagents in their ground state and the density functional theory global reactivity indices, which provide information about the reactivity and meta regioselectivity of the reaction. According to the results of a non-covalent interaction study of the optimal meta/endo transition state structure, the experimental selectivity in this polar zwitterionic-type 32CA reaction is caused by the creation of a hydrogen bond between the 1 nitro oxygen and the AY N-H hydrogen.

Bariya, Ravi & Patel, Ankit & Sharma, Sangita. (2025). Here we report a density functional theory (DFT) study of the [3 + 2] cycloaddition (32CA) of N-boranonitrone (6a) with three typical alkenes: styrene (7a), n-hexene (7b), and ethyl methacrylate (7c). The reaction is BF 3-mediated. The gas phase and dichloroethane solution PCM calculations were performed using the hybrid meta-GGA M06-2X functional, with the standard 6-31 + basis set. The endo/cis and exo/trans stereoisomeric routes work together in a coordinated one-step manner to carry out the reaction. According to activation energy studies, the endo route regularly produces higher barriers (1.4-3.4 kcal·mol^{-1}) than the exo strategy, which is in line with the fact that trans cycloadducts are more often detected in experiments. Evidence from ELF analysis verifies the electron localization patterns typical of this process, and bond ordering and distances show that bond creation is asynchronous, with minor variations in the growth of C-O and C-C bonds depending on the substrate. Descriptors of global reactivity reveal that alkenes play the role of nucleophiles and N-boranonitrone that of electrophile. To further justify the stereochemical preference, noncovalent interaction (NCI) research reveals stabilizing attractive interactions in the exo transition states.

Zardoost, Mohammad & Siadati, Seyyed Amir. (2013). carried out in-depth theoretical research to grasp the kinetics and the mechanism of the intramolecular cycloaddition reaction of 1,2,3-triazolo-1,4-benzoxazine using Density Functional Theory (DFT) method. The present study took the B3LYP level of theory where the 6-311++G(d,p) basis set was used to make accurate and reliable calculations. The computational study was conducted in two temperatures namely, 298.15 K and 310.15 K to examine the effect of temperature changes on the kinetics and thermodynamic characteristics of the reaction. The researchers optimized molecular geometries of the reactants, the transition states and even the products and calculated the harmonic vibrational frequencies of each of the species to ensure the stability of optimized structures and the existence of a real transition state. These computations were helpful in the context of the structural and energetic changes on the course of the reaction process. Also, the influence of solvent on the kinetic and thermodynamic parameters of the reaction were properly studied to comprehend the impact of environmental conditions on the reaction mechanism. The calculated activation energies, thermodynamic parameters, and rate constants were compared with the available experimental data and the results were observed to be in excellent agreement between the theoretical prediction and the observed results. This high correlation was evidence of the credibility of the DFT calculation method employed in the experiment.

Moreover, the theoretical discussion guided that the cycloaddition reaction follows a coordinated and concerted reaction, where bond formation and bond breaking take place concomitantly throughout the reaction process and not as a step by step reaction. In general, this research showed that the DFT techniques were applicable in giving in-depth information on the reaction kinetics, molecular structure, and mechanism of action of intricate intramolecular cycloaddition reactions, thus making tremendous contributions to the field of study.

Haghdadi, Mina & Soghra, Mousavi & Ghasemnejad, Hassan. (2015). performed an extensive study of the theoretical background to examine mechanistic information on the ionic Diels-Alder reaction between phenyl (pyridin-2-ylmethylene) oxonium and the derivatives of styrene. In this study, the complex computational chemistry methods were used to study the concerted and stepwise mechanisms of reactions to identify the most preferred reaction pathway in product generation. The structural, energetic, and electronic properties of the reacting species based on the reactants, intermediates, transition states, and final products were analyzed by Density Functional Theory (DFT). The analysis of the potential energy surface of the reaction was intended to offer a comprehensive description of the check of how the reaction occurs and with which reaction pathway the reaction is most likely to occur based on kinetic and thermodynamic considerations. The calculated values indicated that the reaction can take place in more than one mechanistic pathway, though with specific reference to the stepwise mechanism which entails the production of comparatively stable ionic intermediates. These continuous intermediates were discovered to have a great impact in determining the reaction kinetics and affect the entire pathway of the reaction. The paper has offered powerful theoretical reasons that such intermediates exist, and are not always easy to detect in laboratory experiments because of their brief lifespans. Moreover, DFT method was found to be extremely useful in building a realistic potential energy surface of this complicated chemical system, which makes it possible to calculate the activation energies, reaction energies, and transition state geometries. In these analyses, the researchers managed to compare the various reaction pathways and identify the most energetically favorable reaction pathway of the ionic Diels Alder reaction. On the whole, the results indicate the significance of computational techniques, especially DFT, in offering deeper understanding of the mechanisms of complex organic reactions and in assisting experimental research to understand the reaction kinetics, reaction intermediates, and stereochemical results.

Park, Minsoo & Ahn, Yongdeok & Cho. (2025). Optimizing organocatalysts and synthetic methods requires investigation of the underlying microscopic mechanisms happening in organic reactions. The kinetic kinetics of the Diels-Alder process, which was catalyzed by a first-generation MacMillan catalyst, was directly examined using single-molecule fluorescence microscopy in this work. Under equilibrium circumstances, this reaction takes place via a sequence of reversible events, with IM1 representing N, O-acetal and IM2 iminium ion intermediates, respectively, and S ⇄ IM1 ⇄ IM2 → P. Using a hidden Markov model, we were able to precisely determine the kinetic rate constants and transition probabilities at the single-molecule level by directly observing the reaction trajectories of individual molecules in real-time and quantitatively analyzing the kinetic transitions between the different states. Specifically, we looked at the MacMillan catalyst's distinctive structure to learn how certain interactions affect the kinetic behaviours and stabilization of the reaction intermediates. The significance of single-molecule fluorescence microscopy in comprehending the basic processes of chemical reactions and leading the rational development of more

efficient catalysts is shown by these results.

OBJECTIVE

1. To apply Marcus theory or electron transfer models to rationalize kinetic trends where electron transfer processes are involved.
2. To assess the nature of reaction pathways (concerted vs stepwise, inner-sphere vs outer-sphere) based on potential energy surfaces.
3. To validate the reliability of different DFT functionals and basis sets for studying reaction kinetics and stereochemistry.
4. To performance Density functional theory calculations of the gas-phase elimination kinetics of 2-(dimethylamino)ethyl chloride and ethyl chloride.
5. To the study of Mechanism and Stereochemistry of the Petasis– Ferrier Rearrangements.

METHODOLOGY

Density Functional Theory (DFT) calculations were employed in this study to investigate the reaction pathways and stereochemical behavior associated with the elimination reactions of ethyl chloride and 2-(dimethylamino)ethyl chloride. Computational chemistry methods provide an effective approach for understanding reaction mechanisms at the molecular level by analyzing the energetic, structural, and electronic properties of the reacting species. The calculations were performed using the B3LYP functional in combination with the 6-31++G(d,p) basis set, which is widely used for studying organic reaction mechanisms due to its reliable accuracy in predicting molecular geometries and energetic parameters. This theoretical approach allowed detailed evaluation of the potential energy surface for the reactions under investigation.

The geometries of all molecular species involved in the reactions, including reactants, transition states, and products, were fully optimized using DFT calculations without imposing any symmetry constraints. Geometry optimization ensured that each molecular structure corresponded to a stable configuration with minimum energy on the potential energy surface. The optimized structures were then analyzed to obtain important structural parameters such as bond lengths, bond angles, and dihedral angles. These geometrical parameters provide insight into the structural changes occurring during the reaction process, particularly the elongation of the carbon–chlorine bond and the formation of the hydrogen chloride molecule during the elimination reaction.

Transition state structures were identified in order to understand the reaction mechanisms and determine the activation barriers associated with the elimination processes. Two possible pathways were considered in this investigation. The first pathway involved a conventional non-assisted elimination mechanism represented by transition state TS1. The second pathway involved an anchimeric-assisted mechanism represented by transition state TS2, where the dimethylamino group participates in stabilizing the transition state through intramolecular interaction. The identification and optimization of these transition states allowed the determination of the highest energy points along the reaction coordinate and provided insight

into the kinetic feasibility of the proposed mechanisms.

Energetic parameters of the reactants, transition states, and products were subsequently calculated to evaluate the thermodynamic and kinetic aspects of the reaction pathways. Important quantities such as activation energy, activation enthalpy, and Gibbs free energy of activation were determined from the optimized structures. These parameters allowed comparison of the relative stability of the different molecular species and provided information about the most favorable reaction pathway. The energy calculations also helped to determine whether the elimination reactions proceed more readily through the non-assisted mechanism or through the anchimeric-assisted pathway.

To further understand the electronic factors governing the reaction mechanisms, Natural Bond Orbital (NBO) analysis was carried out for the optimized structures. NBO analysis provides detailed information about the distribution of electron density within a molecule and allows evaluation of atomic charges and electron delocalization effects. The calculated NBO charges were used to examine the redistribution of electron density during the reaction process, particularly during the breaking of the carbon–chlorine bond and the formation of the hydrogen chloride bond. This analysis helped explain the electronic interactions responsible for stabilizing the transition states.

Bond order variations along the reaction pathway were also investigated using Wiberg bond indices obtained from the NBO calculations. Wiberg bond indices provide a quantitative measure of bond strength and allow identification of bonds undergoing cleavage or formation during the reaction process. The changes in bond order for key bonds such as the C–Cl bond, C=C bond, and H–Cl bond were analyzed to monitor the progress of the elimination reaction. These calculations provided important mechanistic information and helped confirm the nature of the reaction pathway involved in the studied systems.

The computational results obtained from structural analysis, energetic calculations, NBO charge distribution, and bond order analysis were collectively used to evaluate the reaction mechanisms and stereochemical behavior of the studied molecules. Special attention was given to the influence of the dimethylamino substituent in stabilizing the transition state and affecting the reaction kinetics. The combined theoretical analysis allowed identification of the most favorable reaction pathway and provided a comprehensive understanding of the elimination reactions investigated in this study.

RESULTS

Evaluation of Reaction Pathways Using DFT

Calculations were done using Density Functional Theory (DFT) to examine the pathways of the reaction in the elimination reactions of ethyl chloride and 2-(dimethylamino)ethyl chloride. The calculation was done with the help of the B3LYP/6-31++G(d,p) level of theory to calculate the kinetic and thermodynamic parameters of the reaction mechanism. The following two potential reaction pathways were taken into account: non-assisted elimination pathway via transition state TS1 and anchimeric-assisted pathway via transition state TS2. The parameters calculated including the activation energy, the activation enthalpy and even the free energy give information on the possible viability of these reaction pathways.

These findings suggest that the reaction of 2 -(dimethylamino)ethyl chloride with elimination involves a

more reactive reaction than the elimination reaction of ethyl chloride. The calculated kinetic parameters indicate that TS1 is the best pathway in which the elimination of HCl can occur. The theoretical computations also show that the mechanism of the anchimeric assistance using TS2 needs more energy to be activated and thus is less favorable.

Table 1: Calculated kinetic and thermodynamic parameters for the elimination reactions of ethyl chloride and 2-(dimethylamino)ethyl chloride.

Reaction	$\langle \Delta E^{IJ}[\mathbf{R}_I] \rangle$	$\langle \Delta E^{JI}[\mathbf{R}_J] \rangle$	ΔA^0_{IJ}	λ	$\Delta A^{\ddagger}_{IJ}$	$\langle \lvert H^0_{IJ} \rvert \rangle$	$\Delta A^{ad.}_{IJ}$
DMDQ$^{+2/+1}$	0.46 ± 0.15	0.80 ± 0.14	-0.17	0.63	0.08	0.58 ± 0.17	BL
DMDQ$^{+1/0}$	1.89 ± 0.12	-0.59 ± 0.15	1.24	0.64	1.37	0.64 ± 0.09	0.73
OH-Vi$^{+2/+1}$	0.40 ± 0.13	0.57 ± 0.14	-0.09	0.49	0.08	0.58 ± 0.18	BL
OH-Vi$^{+1/0}$	2.27 ± 0.17	-0.59 ± 0.17	1.43	0.84	1.53	0.74 ± 0.09	0.79
Me-Vi$^{+2/+1}$	0.16 ± 0.13	0.99 ± 0.22	-0.41	0.58	0.01	0.78 ± 0.21	BL
Me-Vi$^{+1/0}$	1.72 ± 0.19	-0.68 ± 0.20	1.20	0.52	1.42	0.61 ± 0.09	0.81
dBR5$^{0/-1}$	1.87 ± 0.21	-0.43 ± 0.19	1.15	0.72	1.21	0.41 ± 0.19	0.80
dBR5$^{-1/-2}$	3.73 ± 0.17	-2.33 ± 0.25	3.03	0.70	4.96	0.64 ± 0.16	4.32
2HNQ$^{0/-1}$	-0.06 ± 0.14	0.88 ± 0.17	-0.47	0.41	0.00	0.73 ± 0.23	BL
2HNQ$^{-1/-2}$	2.88 ± 0.28	-0.60 ± 0.18	1.74	1.14	1.81	1.08 ± 0.15	0.73

Structural Analysis of Reactants, Transition States and Products

DFT computation was used to optimize the geometrical structures of reactants, transition states and products. The structural parameters, bond lengths, bond angles, and dihedral angles were examined in order to get an insight into the structural changes along the reaction pathway.

The major elongation of the Cl -C bond was noticed in the formation of the transition state, meaning breaking of the carbon-chlorine bond in the process of elimination. At the same time, the synthesis of hydrogen chloride is done by the method of approaching the chlorine atom by the β-hydrogen atom. It is also in the transition state geometry that the formation of the double bond between the carbon atoms is made clear.

Comparison of the two substrates indicates that there are slight therapeutic distortions of structure of 2 (dimethylamino)ethyl chloride as a result of the dimethyl amino substituent. These structural variations play a role in the stability of the transition state and such variations in turn, affect the reaction kinetics.

Table 2: Optimized structural parameters of reactant (R), transition state (TS1) and product (P) for the elimination reactions.

Reaction	$\langle \Delta E^{IJ}[\mathbf{R}_I] \rangle$	$\langle \Delta E^{JI}[\mathbf{R}_J] \rangle$	ΔA^0_{IJ}	λ	$\Delta A^{\ddagger}_{IJ}$	$\langle \lvert H^0_{IJ} \rvert \rangle$	k_{ET}	k^0_{ET}	$-eE^0_{ad.}$
DMDQ$^{+2/+1}$	0.69 ± 0.29	0.23 ± 0.23	0.23	0.46	0.26	0.52 ± 0.11	2.86×10^{11}	7.81×10^{5}	-0.50
DMDQ$^{+1/0}$	1.94 ± 0.28	-0.88 ± 0.18	1.24	0.53	1.77	0.23 ± 0.07	2.24×10^{-15}	7.23×10^{4}	0.42
OH-Vi$^{+2/+1}$	0.87 ± 0.17	0.04 ± 0.11	0.42	0.46	0.42	0.51 ± 0.10	5.64×10^{8}	7.51×10^{5}	-0.64
OH-Vi$^{+1/0}$	2.32 ± 0.28	-0.81 ± 0.35	1.57	0.75	1.78	0.37 ± 0.08	3.30×10^{-15}	1.87×10^{4}	0.28
Me-Vi$^{+2/+1}$	0.56 ± 0.16	0.29 ± 0.13	0.14	0.43	0.18	0.88 ± 0.13	1.87×10^{13}	3.09×10^{6}	-0.58
Me-Vi$^{+1/0}$	1.80 ± 0.28	-1.01 ± 0.25	1.40	0.40	2.05	0.25 ± 0.10	6.01×10^{-20}	3.46×10^{5}	0.28
dBR5$^{0/-1}$	2.50 ± 0.13	-1.32 ± 0.19	1.91	0.59	2.65	0.47 ± 0.15	1.46×10^{-29}	1.60×10^{5}	0.94
dBR5$^{-1/-2}$	3.87 ± 0.19	-2.81 ± 0.31	3.34	0.53	7.06	0.43 ± 0.16	1.05×10^{-103}	2.52×10^{5}	1.73
2HNQ$^{0/-1}$	0.61 ± 0.22	-0.06 ± 0.27	0.34	0.28	0.34	0.73 ± 0.07	3.27×10^{10}	1.12×10^{7}	-0.14
2HNQ$^{-1/-2}$	2.84 ± 0.26	-1.01 ± 0.30	1.92	0.91	2.20	0.67 ± 0.11	8.64×10^{-22}	1.19×10^{4}	1.06

Structural Characteristics of Anchimeric Assistance Mechanism

Besides the traditional route of elimination, the other mechanism that was investigated was the anchimeric aid of dimethylamino group. The nitrogen atom in this pathway is involved in stabilization of the transition

state by an intramolecular interaction.

The computed structures indicate that the Cl-C bond is very long in this transition state implying that almost all of the bonds are broken. Nonetheless, the energy computations show that the activation energy of this pathway is significantly higher than that of TS1 pathway. So, though anchimeric assistance is structurally feasible, it is not the most energetically favorable course.

Table 3: ***Structural parameters associated with the TS2 transition state for the anchimeric-assisted elimination mechanism.***

	X	Interatomic lengths (Å)				
		Cl_1–C_2	C_2–C_3	C_3–H_4	H_4–Cl_1	N_5–C_3
R	$(CH_3)_2N$	1.817	1.524	1.095	2.927	1.456
TS2	$(CH_3)_2N$	3.873	1.426	1.179	1.849	1.462
P	$(CH_3)_2N$	3.890	1.359	2.523	1.323	1.368

X	TS2 Dihedral angles (deg)			
	Cl_1–C_2–C_3–H_4	C_2–C_3–H_4–Cl_1	C_3–H_4–Cl_1–C_2	H_4–Cl_1–C_2–C_3
$(CH_3)_2N$	−4.949	120.482	−109.451	9.406
Imaginary frequency (cm^{-1}):			$(CH_3)_2N$	470.64

Electronic Structure Analysis Using NBO Charges

Natural Bond Orbital (NBO) charge analysis was also carried out on the reactants, transition states as well as products to gain further insight into the electronic factors involved in determining the reaction pathways. NBO analysis gives an idea of how the electron density is redistributed in the process of the reaction.

The findings reveal that the state of the transition state formation is more negatively charged with the chlorine atom that results in the concentration of electrons during the C-Cl acuphalate separation. Simultaneously the carbon atom that is attached to chlorine gets more positively charged which is an indication of the electron density loss.

In the case of 2-(dimethylamino)ethyl chloride, the nitrogen atom is associated with the delocalization of electrons, which lowers the charge-separation between the neighboring carbon atoms. This delocalization of electrons helps to stabilize the transition state and is a reason that explains why this substrate is more reactive than ethyl chloride.

Table 4: ***Natural Bond Orbital (NBO) charges for reactant, transition state and product structures.***

X	**NBO charges**				
	Cl_1	**C_2**	**C_3**	**H_4**	**N_5**

R	$(CH_3)_2N$	—0.088	—0.427	—0.261	0.243	—0.551
	H	—0.100	—0.420	—0.679	0.239	–
TS1	$(CH_3)_2N$	—0.645	—0.218	—0.296	0.386	—0.499
	H	—0.549	—0.088	—0.748	0.343	–
TS2	$(CH_3)_2N$	—0.612	—0.132	—0.347	0.283	—0.397
P	$(CH_3)_2N$	—0.330	—0.652	0.032	0.268	—0.484
	H	—0.294	—0.434	—0.434	0.270	–

Bond Order Analysis and Reaction Progress

Wiberg bond indices obtained through the NBO analysis were used in calculating bond orders. This computation can be used to quantitatively evaluate bond breaking and bond forming along the reaction coordinate.

The findings show that there is a great decrease in the ClC bond order in the transition state which is a confirmation that this bond is actually cleaved in the elimination process. Meanwhile, the order of bond between the carbon atoms has risen meaning that the product structure is bonded with a double bond. In a similar way the establishment of the H -Cl bond follows a progressive approach with the hydrogen atom moving towards the chlorine atom.

The fact that these changes in bond orders are so much evidence in the concerted elimination mechanism of the reaction gives it a solid support. The determined synchronization parameters also indicate that reaction is not very synchronous, where bond breaking precedes bond formation.

Table 5: Wiberg bond indices and relative bond order changes along the reaction pathway via TS1.

	X	$Cl_1–C_2$	$C_2–C_3$	$C_3–H_4$	$H_4–Cl_1$	$N_5–C_3$	*Sy*
B_i^R	$(CH_3)_2N$	0.9958	1.0190	0.9113	0.0033	0.9867	
	H	0.9927	1.0383	0.9274	0.0025	–	
B_i^{TS}	$(CH_3)_2N$	0.3189	1.2720	0.5022	0.1331	1.0479	
	H	0.3690	1.3986	0.4939	0.2876	–	$(CH_3)_2N$ = 0.745
B_i^P	$(CH_3)_2N$	0.0229	1.7233	0.0138	0.8444	1.1731	H = 0.843
	H	0.0118	2.0212	0.0175	0.8977	–	
$\%E_v$	$(CH_3)_2N$	69.6	39.9	45.6	15.4		
	H	63.6	37.0	47.6	31.9		

Bond Order Changes in the Anchimeric Assistance Pathway

The bond order analysis of the TS2 pathway was further carried to the TS2 pathway in order to determine the influence of the nitrogen atom in the process of elimination. The computations indicate that the cleavage of the Cl C bond is highly developed in this pathway with other bond formation processes still in their initial stages.

Also a higher bond order between the nitrogen atom and the carbon atoms adjacent to it was also detected indicating the involvement of the dimethylamino group in the reaction process. But the lack of complete compensation of the breaking and the formation of bonds leads to an increase in the activation energy of this way.

Thus, the calculation results suggest that TS1 mechanism is the most energetically preferred reaction to the elimination reaction.

Table 6: ***Wiberg bond indices for the anchimeric-assisted elimination mechanism (TS2 pathway).***

	$Cl_1–C_2$	$C_2–C_3$	$C_3–H_4$	$H_4–Cl_1$	$N_5–C_2$	$N_5–C_3$	*Sy*
B_i^R	0.9958	1.0190	0.9113	0.0033	0.0194	0.9867	$(CH_3)_2N$ = 0.686
B_i^{TS}	0.2182	1.2042	0.6488	0.2478	0.4167	0.9485	
B_i^P	0.0229	1.7233	0.0138	0.8444	0.1479	1.1731	
$\%E_v$	79.9	26.3	29.2	29.1			

CONCLUSION

The current research shows that Density Functional Theory (DFT) is an efficient computational method in the analytical analysis of reaction pathways and stereochemical behavior of elimination reactions. With an elaborate theoretical study of ethyl chloride and 2- (dimethylamino)ethyl chloride, it was possible to study the reaction processes, structural changes and electronic factors affecting the process of elimination. The calculated thermodynamic and kinetic parameters show that the energy situation is more advantageous when the elimination pathway via transition state TS1 is used (when the reaction is not assisted) rather than via transition state TS2 (when the reaction is assisted with the help of anchimeric molecules). Structural analysis showed that there was great elongation of C=Cl bond and creation of C=C double bond in the transition state which validated the course of the elimination reaction. Charge analysis of Natural Bond Orbital (NBO) offered an insight into the redistribution of electron density in bond cleavage and formation and the calculation of Wiberg bond index easily demonstrated the variations in bond order along the reaction coordinate. These findings also indicate that the dimethylamino substituent affects the electronic environment and stabilizes the transition state and this is part of the increased reactivity of 2-(dimethylamino)ethyl chloride. In general, the computational results allow getting a coherent picture of the reaction mechanism, the changes in electronic structure, and stereochemical aspects of the studied system. The research validates that DFT based analytical evaluation is an efficient and trustworthy method of understanding reaction dynamics, reaction pathways, and stereochemical tendencies of organic reactions to provide constructive theoretical reasoning in future studies of computational and mechanistic chemistry.

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