

Tunneling Study of H-atom transfer reactions

Project report Submitted to the IISER Pune
for the Degree of
BS-MS
in
CHEMISTRY

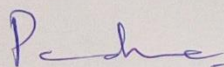


K Siddhartha (Roll No. 20151018)

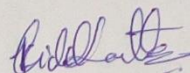
<p>Supervisor: Dr D Annapurna Padmavathi Department of Chemistry, University College of Science, Osmania University, Hyderabad</p>	<p>Expert: Dr Anirban Hazra Associate Professor, Indian Institute of Science Education and Research</p>
---	--

Certificate

This is to certify that this dissertation entitled "**Tunnelling study of H-atom transfer reactions**" towards the partial fulfilment of the BS-MS dual degree programme at the Indian Institute of Science Education and Research, Pune represents study/work carried out by "K Siddhartha at Osmania University under the supervision of "Dr D.A. Padmavathi, Associate professor, Department of Chemistry" during the academic year 2020-2021.

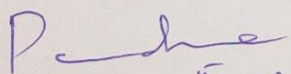

30th Oct 2021

Asso. Professor
Department of Chemistry
Osmania University
HYDERABAD - 500 007


K. Siddhartha
20151018

Declaration

I hereby declare that the matter embodied in the report entitled "**Tunnelling study of H-atom transfer reactions**" are the results of the work carried out by me at the Department of Chemistry, Osmania University, under the supervision of "Dr D.A. Padmavathi, Associate professor" and the same has not been submitted elsewhere for any other degree.


30th Oct 2021

Asso. Professor
Department of Chemistry
Osmania University
HYDERABAD - 500 007

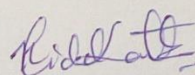

K. Siddhartha
20151018

Table of Contents		Page No.
1	Abstract	3
2	List of Tables	4
3	List of Figures	5
4	Acknowledgement	6
5.	Introduction	7
6.	Kinetic Isotope Effects	9
7.	Computational Chemistry	11
8.	Results and Discussion	13
9.	Conclusions	32
10.	References	34
11	Objectives met and concepts learnt during the tenure of the project	36

Abstract

Tunneling phenomenon not only can control but can also drive chemical reactions in directions unexpected from traditional theories. Tunneling picks up a reaction path that results in temperature-independent rate constants at low temperature with enhanced kinetic isotope effects. Here an attempt is made to understand tunnel effect in H-atom transfer reactions through computations.

List of Figures		Page No.
Fig 1.	Origin of tunneling: A graphical explanation	8
Fig 2.	Schematic representation of isotopic substitution of a reaction	9
Fig 3.	Morse potential energy curve for C-H and C-D zero point energies(ZPE) in calculation of kH/kD ratios using vibrational frequencies. Heavier isotope has lower ZPE.	10
Fig 4.	Temperature dependence of rate constant	11
Fig 5.	Names of reactions	14
Fig 6.	[1,5]- intramolecular sigmatropic Hydrogen shift reactions (1,3 Pentadiene \leftrightarrow 2,4 Pentadiene), and also it's halogen substituents.	17-19

List of Tables		Page No.
1.	Table 1: <i>Energies in kcal/mol relative to reactants and saddle point of the H-shift reactions (ΔE_R- ΔE_{TS})</i>	15
2.	Table 2: <i>Comparison of computed activation energy with that of experimental data[12]</i>	16
3.	Table 3: The isotopic substitution based rate constants K_H/K_D calculated using $\frac{k_H}{k_D} = e^{\frac{hc(1-\sqrt{1/2})\bar{\nu}_H}{KT}}$ and polyrate	21
4.	Table 4: The isotopic substitution based rate constants K_H/K_D calculated using $\frac{k_H}{k_D} = e^{\frac{hc(1-\sqrt{1/2})\bar{\nu}_H}{KT}}$	22
5.	Table 5.1 Manual and Polyrate graphs	23-31

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude and profound thanks to my teacher and thesis supervisor Dr D A Padmavathi, Associate Professor, Department of Chemistry, University College of Science, Osmania University, Hyderabad for her guidance, constant encouragement and valuable suggestions throughout my MS study and related research. I am very much thankful for her support, affection, which helped me a lot in exploring my abilities and made it possible for me to carry out the present work which otherwise, would have been very difficult.

I wish to express my sincere thanks to Dr Anirban Hazra, Associate Professor, IISER Pune, for his support, expert guidance, his precious suggestions and valuable comments to improve upon the thesis for it to be in the current state.

I thank IISER Pune for all the support extended to me for completion of the project.

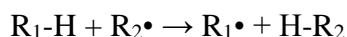
I am also thankful to the Head, Department of Chemistry, Osmania University for providing me facilities to carry out the work in the department.

Finally, I thank my senior Mr A Srikanth for all the help he provided me during my project.

Introduction

Hydrogen abstraction reactions with radicals are of great importance in organic chemistry and biology. The gas phase oxidative reactions of volatile organic molecules in atmosphere, combustion reactions, dimerization reactions, enzyme catalyzed proton transfer processes, numerous functional isomerization based biological processes are of special interest as they undergo radical mediated H-atom abstraction.

These Hydrogen atom transfer reactions originate by abstracting a proton and an electron in a single kinetic step from carbon when a saturated organic molecule reacts with a free radical.



In the above reaction R_1 and R_2 can be alkyl or aryl group. During H-abstraction the selectivity of the free radicals towards C-H bonds of different types is determined by bond dissociation energy and polar effects. The rate of the abstraction process increases as bond dissociation energy decreases. The mechanism of these H atom transfer reactions is not very well understood as the existing semi classical theories failed to explain the experimental findings. The increasing experimental evidence of quantum tunneling effects at atomic and molecular level revealed by NMR, EPR and mass analytical techniques make H-transfer reactions more inquisitive and interesting. Tunneling phenomenon not only can control but can also drive chemical reactions in directions unexpected from traditional theories. Experiments in combination with powerful computational approaches, made scientists to realize that quantum mechanical tunneling must be a significant factor to fully understand many chemical reactions involving H-atom transfer reactions, and even whole molecule reactions [1].

Chemical reactivity and selectivity are understood through Transition state theory (TST). It treats chemical kinetics in terms of a potential energy surface (PES), wherein reactants and products are

connected by TS. Tunneling is Quantum mechanical phenomenon where the wave-function for the molecule penetrates through the energetic barrier rather than over it Fig 1. This effect commonly referred to as quantum mechanical tunnelling (QMT) is directly related to the inherent wave character of particles, allowing them to pass through their surrounding potential energy barriers. De Broglie wavelength for a number of particles reveal that tunnelling is more likely to happen with decrease in particle size. As λ approaches the scale of chemical reactions (within 25nm-30nm) tunnelling becomes a factor in reaction mechanism (ex. λ H is 0.7 Å for Kinetic energy is around 20 kJ/mole).

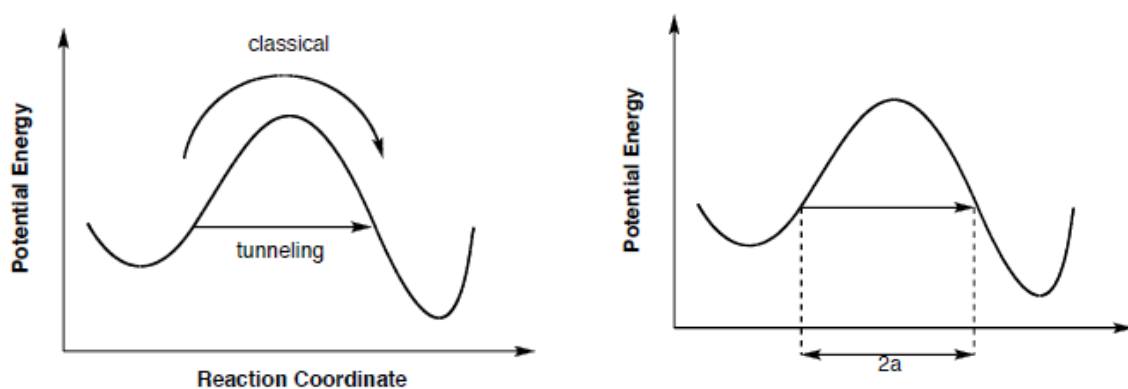


Fig.1 Origin of tunneling: A graphical explanation

Reactants must have a certain energy to surmount the activation barrier to reach products along the reaction coordinate Fig.1. R. P Bell modified Arrhenius equation [2,3,4,5]

$$k = A e^{-\frac{E}{RT}} \dots\dots\dots (1)$$

and included a quantum chemical correction factor Q and explored its effect on Arrhenius treatment of reaction kinetics (eqn.2).

$$k = QA e^{-E/RT} \dots\dots\dots (2)$$

$$\text{Where } Q = \frac{e^\alpha}{\beta - \alpha} (\beta e^{-\alpha} - \alpha e^{-\beta} ; \alpha = \frac{E}{RT} ; \beta = \frac{2a\pi^2(2mE)^{1/2}}{h}$$

Equation 2 relates measurable reaction parameters to the probability of tunneling and helps us to evaluate tunneling probability through the barrier width 2a Fig.1.

Theoretically the rate of a chemical reaction is obtained from the computation of the transmission coefficient through a potential energy barrier, where the height of the barrier corresponds to the activation energy. The term β is very sensitive to the mass of the tunnelling particle, for example when Hydrogen is isotopically substituted with Deuterium H atom can tunnel more readily than D. So, rate constant k evaluation for both hydrogen and its isotope deuterium can indicate tunneling phenomenon and this study is kinetic isotope effect.

Kinetic isotope effects

A kinetic isotope effect is a mechanistic phenomenon wherein isotopically substituted molecules react at different rates. Isotopic substitution does not affect the potential energy surface of the reaction or the energies of the electronic states. Only mass dependent properties are affected, most importantly vibrational frequencies of the molecular bonds participating in the reaction. (Ex. C-H bonds or C-D bonds if isotopically substituted) Fig2.

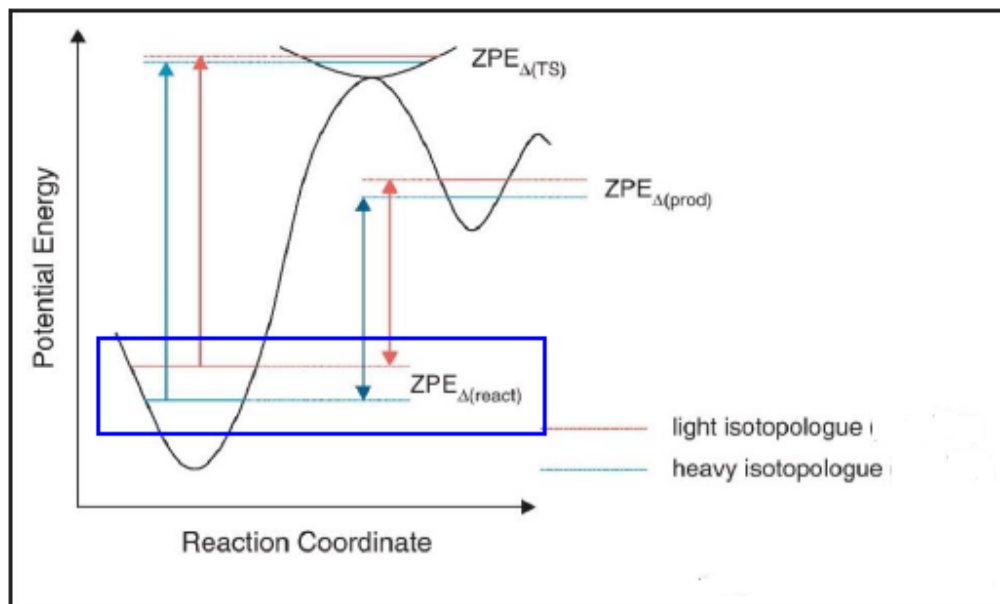
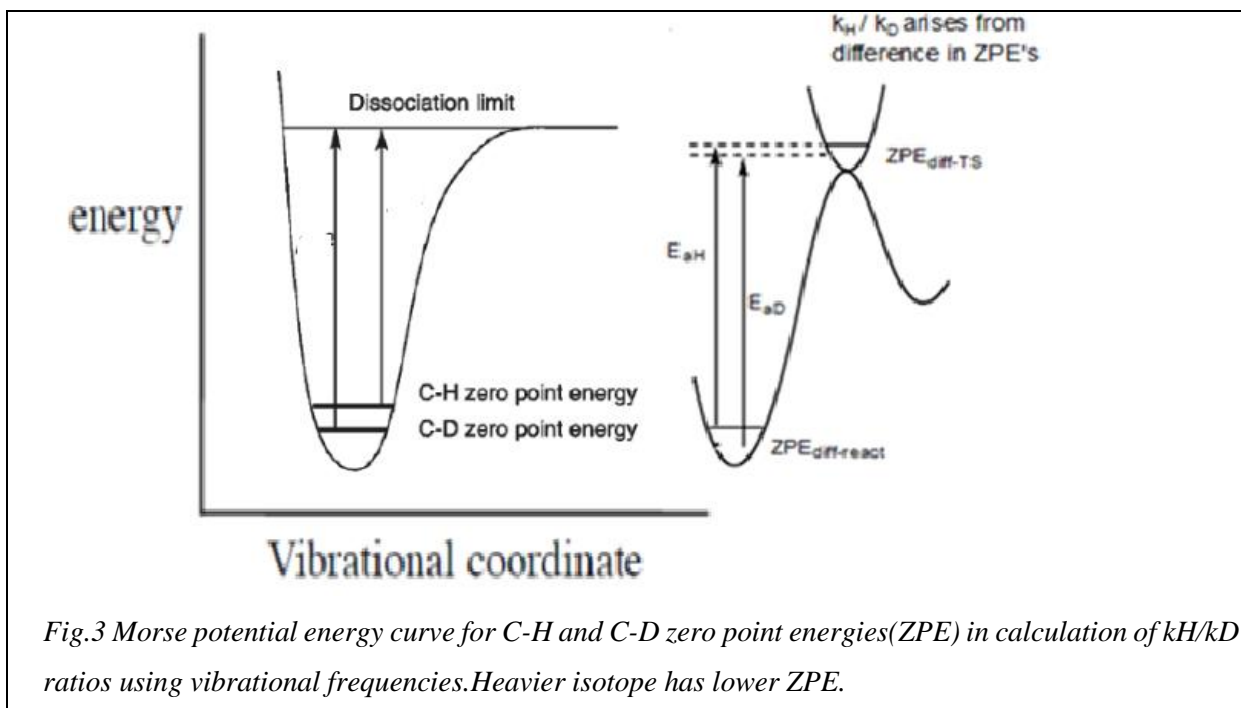


Fig2. Schematic representation of isotopic substitution of a reaction

So, a kinetic study through isotopic substitution of the reactant(s) can result in a significant difference in zero-point vibrational energy ZPVEs between reactants and TS Fig.2.

The zero-point vibrational energy for any vibrating molecule is given by $E = \frac{1}{2}h\nu_o$. Energy difference for the frequency of vibration transition state is given by $\Delta E = -\frac{1}{2}h(\nu_H - \nu_D)$ since $\nu = \frac{c}{\lambda}$ and $\bar{\nu} = \frac{1}{\lambda}$ where $\bar{\nu}$ is wave number



$$\Delta E = -\frac{1}{2} hc(\bar{\nu}_H - \bar{\nu}_D) \text{ since } \nu_D = \sqrt{\frac{1}{2}} \nu_H$$

$$\Delta E = -\frac{1}{2} hc(\bar{\nu}_H - \sqrt{\frac{1}{2}} \nu_H) \dots\dots\dots (3)$$

since energy does not change with isotopic substitution kinetic isotopic effect can be studied using

$$\frac{k_H}{k_D} = e^{\frac{hc(1-\sqrt{1/2})\bar{\nu}_H}{KT}} \dots\dots\dots(4)$$

Due to mass dependence of the vibrational energy, deuterium isotope exchange results in difference in activation barriers and thus different reaction rates, which is called the kinetic isotope effect (KIE = K_H/K_D) Fig. 3. KIE's provide a uniquely sensitive probe of transition state structures and provide valuable information about the rate determining step in reaction mechanisms.

This concept is strictly associated with kinetic control and allows the explanation of chemical reactivity and selectivity in an intuitive way [4,5].

A better insight into QMT can be obtained by studying reactions at low temperatures which result in a curvature of Arrhenius plots in the low temperature regime *Fig. 4*. At higher temperatures log of rate constant varies linearly with $1/T$ and merges with the classical over barrier rate, resulting in lowered activation barriers derived by Arrhenius plots. But, in low temperature regime, temperature independence of rate constant, leads to QMT's significance on the overall reaction rate.

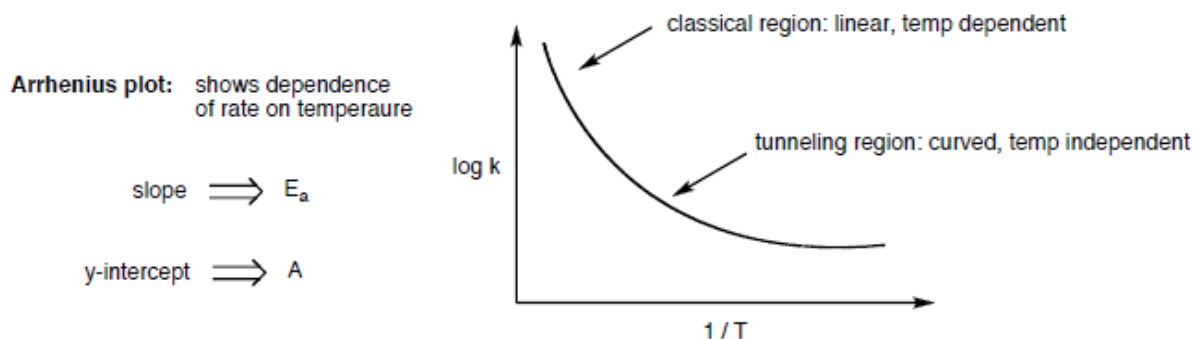


Fig 4: temperature dependence of rate constant

Four key experimental observations that imply quantum tunneling is taking place in chemical reactions are large kinetic isotope effect, temperature independence, anomalous A (Arrhenius factor) values and anomalous activation energy E_a values.

Computational Chemistry

Computational chemistry is devoted to study, rationalize, predict and gain insight into the molecular structure using mathematical approximations and computer programs. Computational calculations help us to investigate the shape of the molecule through geometry optimization, molecular spectra through frequency data, stability and reaction mechanism through single-point energy. From the computed electronic structure data, one can deduce the frequencies of the optimised state, transition states, reaction paths, rate constants and energy of activation for chemical reactions, heats of reactions in thermodynamics, binding ability of ligand with protein (docking) etc. The accuracy

level and the time of computation of the calculation is governed by the computational method used. The vibrational frequencies within the molecule can lead to the calculation of thermodynamic variables like heats of formation ΔH , entropy changes ΔS and the free energy values ΔG . There are two approaches to arrive at minimum energy; those that use Schrödinger's equation and those that do not. Based on each approach there are various available computational tools [4,5,6,7]. Each tool is a system of equations modelled as computer programs. Different tools use different approximations, towards molecular energetics and produce results of varying levels of accuracy. Here we use Density functional methodology to study the current project of H-atom tunneling in radical reactions. The program Polyrate 17-C is used to evaluate ratios of rate constants [14]. Polyrate 17-C is designed to be used in conjunction with interfaces to electronic structure calculations for direct dynamics. GAUSSIAN 09[6] electronic structure package is used in conjunction with Polyrate to evaluate kinetic isotope effects.

Polyrate is a computer program for the calculation of chemical reaction rates of polyatomic species (and also atoms and diatoms as special cases) by variational transition state theory (VTST); conventional transition state theory is also supported. Bimolecular and unimolecular reactions and gas-phase, solid-state, and gas-solid-interface reactions are included. Cartesian coordinate will very likely yield imaginary frequencies along the reaction coordinate, or a variationally optimized reaction path and to add multidimensional tunnelling contributions by means of a transmission coefficient; the treatment of loose transition states is based on variable reaction-coordinate VTST with single-faceted and multifaceted dividing surfaces. Vibrational frequencies may be scaled or unscaled (it is highly recommended to scale the frequencies along the reaction coordinate by a scale factor that is developed for reproducing accurate ZPE).

The program polyrate was used to perform kinetic studies of H transfer reactions at various temperatures to understand isotopic substitution effect for reactions. The thermochemistry data obtained from Gaussian is used as input to polyrate to calculate kinetic isotopic ratio K_H/K_D .

Results and Discussion

The geometry of the molecules are calculated using Density Functional Theory and the computed results concerning molecular geometric structure in ground state are obtained using (B3LYP/6-31G(d,p)) functional [6,7]. The identified Hydrogen atom transfer reactions chosen for tunneling study are listed in Fig 5. [8-12]. The frequencies of the optimized state, transition states, reaction paths, rate constants and energy of activation for chemical reactions, heats of reactions and Gibbs free energy data is calculated, using Gaussian 09W program package. Frontier molecular orbitals are visualized using Gaussview15 Version 5.0. The present work aims a detailed study to find out the role of H-atom tunneling in Hydrogen shift reactions.

Initially, the transition state calculations are performed for [1,5]- intramolecular sigmatropic Hydrogen shift reactions [8] (1,3 Pentadiene \leftrightarrow 2,4 Pentadiene), along with it's halogen substituents in suprafacial mode (Scheme 1) Fig. 5. The calculation of thermodynamic variables like heat of formation ΔH , entropy changes ΔS and free energy values ΔG are calculated from thermochemistry data of reactants relative to saddle points (for example $\Delta E_{TS} - \Delta E_R$) and are reported in **Table 1**. The comparison of theoretically obtained activation energy with that of experimental data [12-14] is shown in **Table 2**. The ball and stick models of the reactant, product and transition state are displayed in Fig.6. Among the sigmatropic rearrangements of fluoro, chloro and bromo pentadienes, it is observed that fluoro pentadiene has higher activation energy when compared to others in the group due to 1,5 hydrogen shift in antra facial mode.

Then, [1,5]-Hydrogen Shifts are studied for cyclohexadiene, 3 Heterocyclic Six-Membered Dienes and two aromatic systems. In cyclohexa-1,3-diene when CH_2 on 6 carbon atom is replaced by heteroatom like O, N or S the intrinsic activation energies (E_a (kcal/mole) for H-Shifts rises. It is displayed as 42.44 for CH_2 , 43.64 for Oxygen, 45.1 for Sulphur and 50.23 for N in Table 1. Also as phenanthrene is highly aromatic we can see a decrease in activation energy when we move from nonaromatic to aromatic systems i.e., cyclohexadiene, pyran, 1,2-dihydropyridene > Indene > Phenanthrene.

Transition state study for four H-abstraction reactions, 3 reactions with with CH_3 radical and one with OH radical are also studied using Gaussian 09 W with B3LYP functional. The reactions are mentioned in Fig 5 and Table 1.

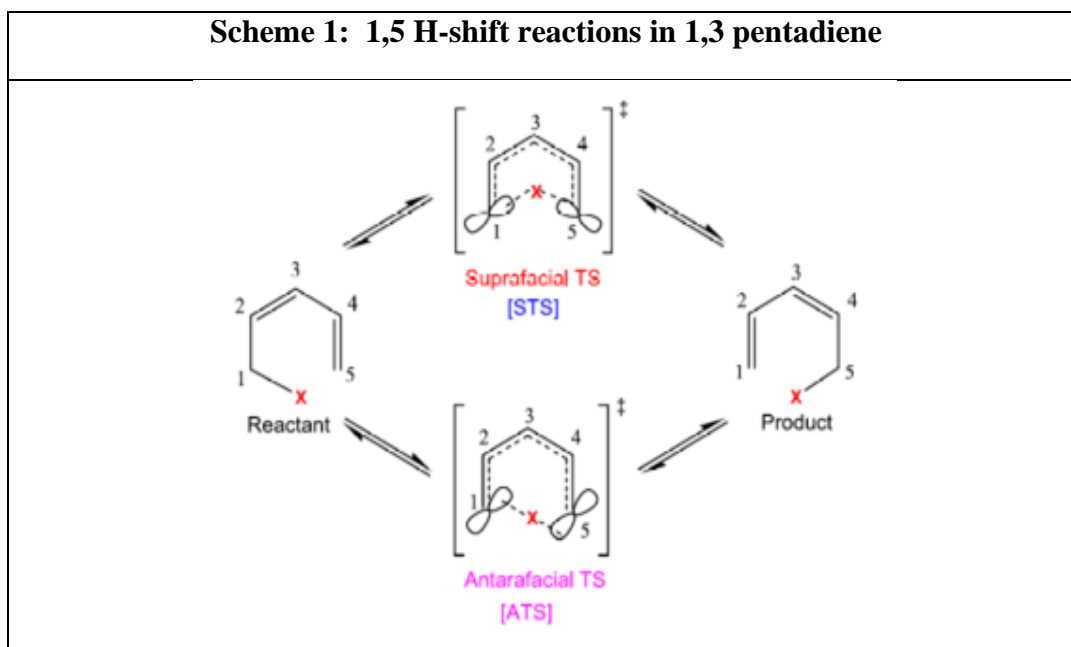


Fig. 5 Names of reactions

[1,5]- intramolecular Hydrogen shift reactions			H-abstraction reactions by radicals	
1	Pentadiene 		8	$\text{CH}_3 + \text{CH}_3\text{CN} \rightarrow \text{CH}_4 + \text{CH}_2\text{CN}$
2	Cyclohexadiene 	5	9	$\text{CH}_3 + \text{CH}_3\text{NC} \rightarrow \text{CH}_4 + \text{CH}_2\text{NC}$
3	Pyran 	6	10	$\text{CH}_3\text{OH} + \text{OH} \rightarrow \text{CH}_2\text{OH} + \text{H}_2\text{O}$
4	Thiopyran 	7	11	$\text{CH}_3\text{OH} + \text{CH}_3 \rightarrow \text{CH}_4 + \text{CH}_2\text{OH}$

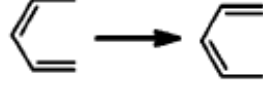



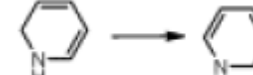


Table 1: Energies in kcal/mol relative to reactants and saddle point of the H-shift reactions ($\Delta E_R - \Delta E_{TS}$)					
	Reaction Type	1,5 Hydrogen shift Reactions			
		ΔE (KCal/Mol)	ΔH (KCal/Mol)	ΔS (KCal/Mol)	ΔG (KCal/Mol)
1a	Pentadiene 	33.61	30.15	6.81	34.85
1b	1-Flouro-3 Pentadiene	49.04	47.05	48.23	4.15
1c	1-Chloro-3 Pentadiene	38.35	37.64	38.18	2.16
1d	1-Bromo-3 Pentadiene	35.38	35.39	35.72	2.85
2	Cyclohexadiene 	42.44	42.43	1.07	42.73
3	Pyran 	43.64	43.64	20.33	43.73
4	Thiopyran 	45.1	45.1	0.17	45.15
5	Dihydro Pyridine 	50.23	50.22	2.96	51.11
6	Phenanthrene 	15.25	15.26	3.09	16.17
7	Indene 	25.15	25.74	1.67	26.15
	Reaction type	Hydrogen abstraction reactions with OH Radicals			
8	$\text{CH}_3 + \text{CH}_3\text{CN} \rightarrow \text{CH}_4 + \text{CH}_2\text{CN}$	8.76	8.76	11.71	12.25
9	$\text{CH}_3 + \text{CH}_3\text{NC} \rightarrow \text{CH}_4 + \text{CH}_2\text{NC}$	27.86	27.86	10.93	24.6
10	$\text{CH}_3\text{OH} + \text{OH} \rightarrow \text{CH}_2\text{OH} + \text{H}_2\text{O}$	23.06	23.05	9.97	26.02
11	$\text{CH}_3\text{OH} + \text{CH}_3 \rightarrow \text{CH}_4 + \text{CH}_2\text{OH}$	22.68	22.56	8.54	24.32

Table 2: Comparison of computed activation energy with that of experimental data [12]

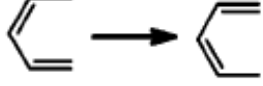
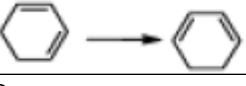

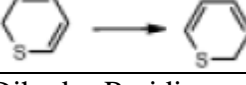


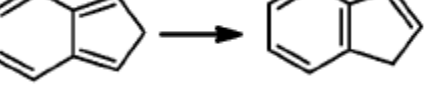
	Reaction type		
	1,5 Hydrogen shift	ΔE (KCal/Mol) DFT	ΔE (KCal/Mol) Experimental [Ref 12]
1	Pentadiene 	33.61	36.3
2	Cyclohexadiene 	42.44	41.7
3	Pyran 	43.64	47.7
4	Thiopyran 	45.1	48.5
5	Dihydro Pyridine 	50.23	49.2
6	Phenathrecene 	15.25	16.6
7	Indene 	25.15	29.0

Fig 6. [1,5]- intramolecular sigmatropic Hydrogen shift reactions (1,3 Pentadiene ↔ 2,4 Pentadiene), and also it's halogen substituents

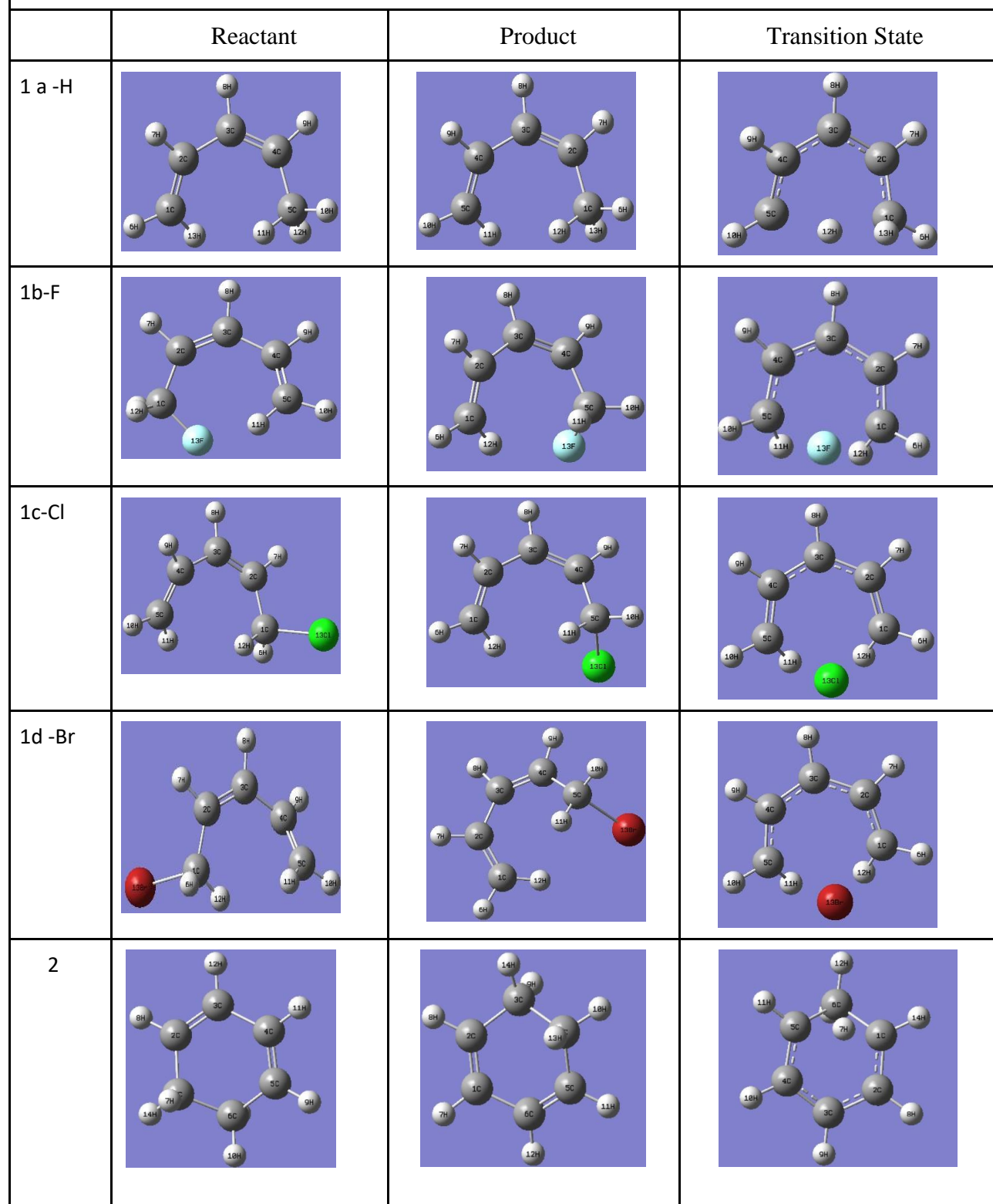
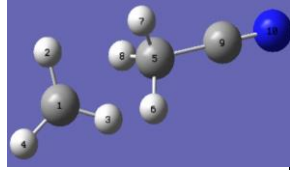
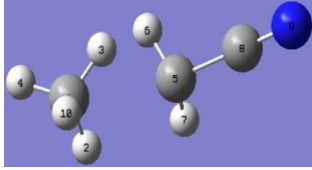
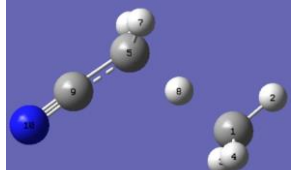
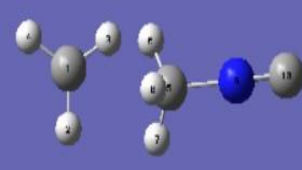
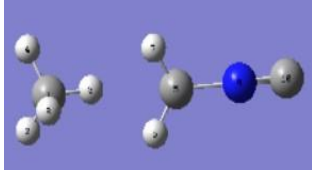
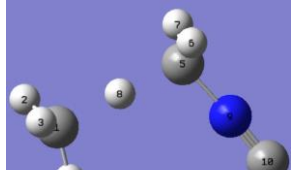
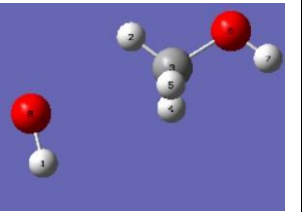
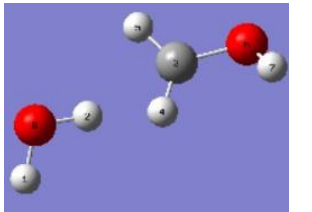
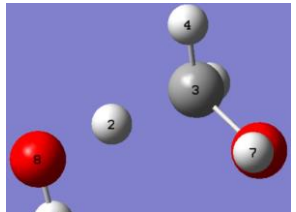
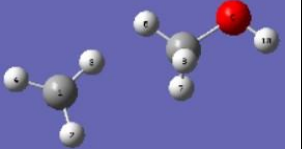
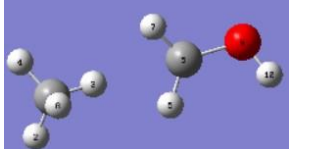



Fig. 6 Contd. [1,5]- intramolecular sigmatropic Hydrogen shift reactions

Names	Reactant	Products	Transition State
3			
4			
5			
6			
7			

Fig. 6 Contd.. Hydrogen abstraction reactions with OH Radicals

Names	Reactant	Products	Transition State
8			
9			
10			
11			

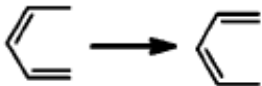
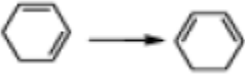





The program **polyrate** was used to understand isotopic substitution effect for all the reactions. The log files generated from transition state calculations using Gaussian are taken and then are given as input to polyrate to calculate kinetic isotopic ratio K_H/K_D . The obtained ratio is then varied using polyrate at various temperatures. Kinetic studies of H transfer reactions at various temperatures (273K to 318K) is performed and K_H/K_D ratio is evaluated. The expected trend was observed for H-shift reactions, and is displayed [**Table 3**]. Subsequently K_H/K_D ratio was computed manually and it showed the expected results i.e increase in K_H/K_D ratio with decrease in temperature T for all reactions. Repetition of kinetic studies of atom transfer reactions at various temperatures (273K to 318K) is performed for all the reactions studied and K_H/K_D ratio is evaluated and displayed in **Table 3**. The graphs related to the plots of K_H/K_D versus T are shown in **Table 4.1 to 4.9**. The activation energy data obtained for radical based reactions is shown in Table 4.

Then, K_H/K_D ratio was computed using polyrate at various temperatures. The manually calculated K_H/K_D values for cyclohexadiene, indene and phenanthracene are matching with that of those calculated from polyrate program. But, Polyrate program showed errors when it was executed for some of the H-abstraction reactions.

Polyrate program was employed to calculate rate constants for radical reactions using 18 different functionals. It was stated that of all the functionals chosen MPWB1K functional (Optimized against kinetic database) was found to be the best to evaluate rate constants than B3LYP functional. So as B3LYP functional is not a suitable function for kinetic studies we were not successful in making best use of polyrate program. [15].

Table 3 The isotopic substitution based rate constants k_H/k_D calculated using

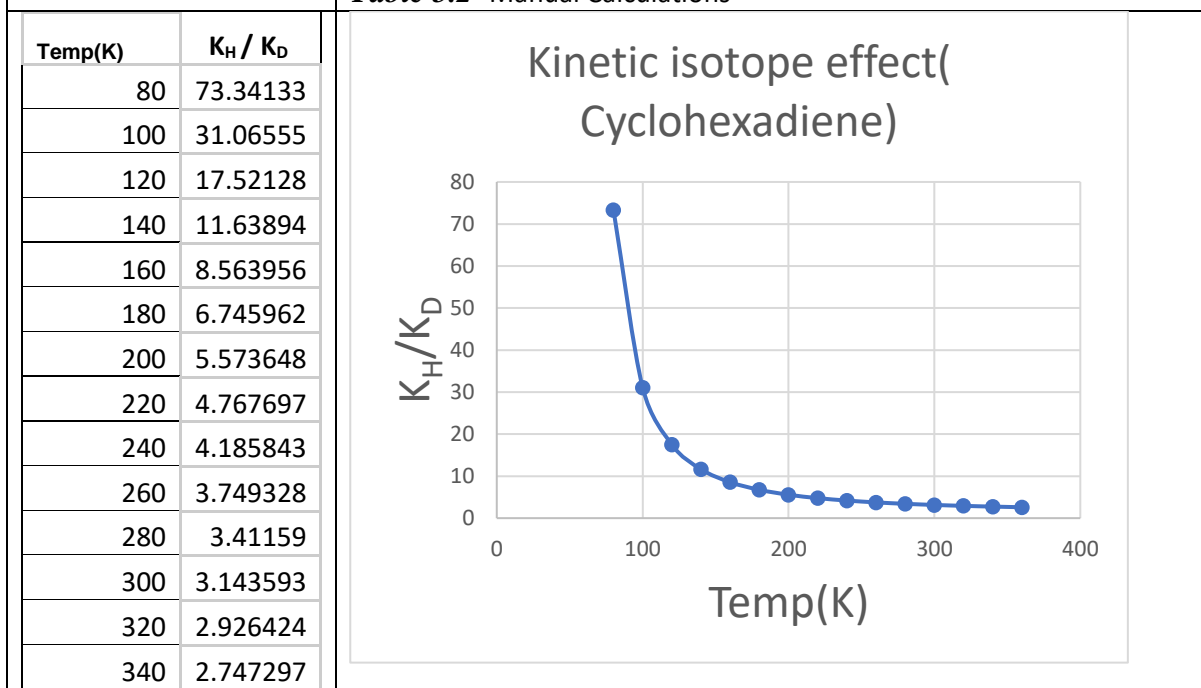
$$\frac{k_H}{k_D} = e^{\frac{hc(1-\sqrt{1/2})\bar{\nu}_H}{KT}} \text{ and polyrate}$$

K_H/K_D		Manual	Polyrate
1	Pentadiene 	2.9	0.997
2	Cyclohexadiene 	3.14	0.045
3	Pyran 	2.5	0.986
4	Thiopyran 	3.27	0.991
5	Dihydro Pyridine 	2.68	0.97
6	Phenathrecene 	2.2	0.98
7	Indene 	2.02	1.06

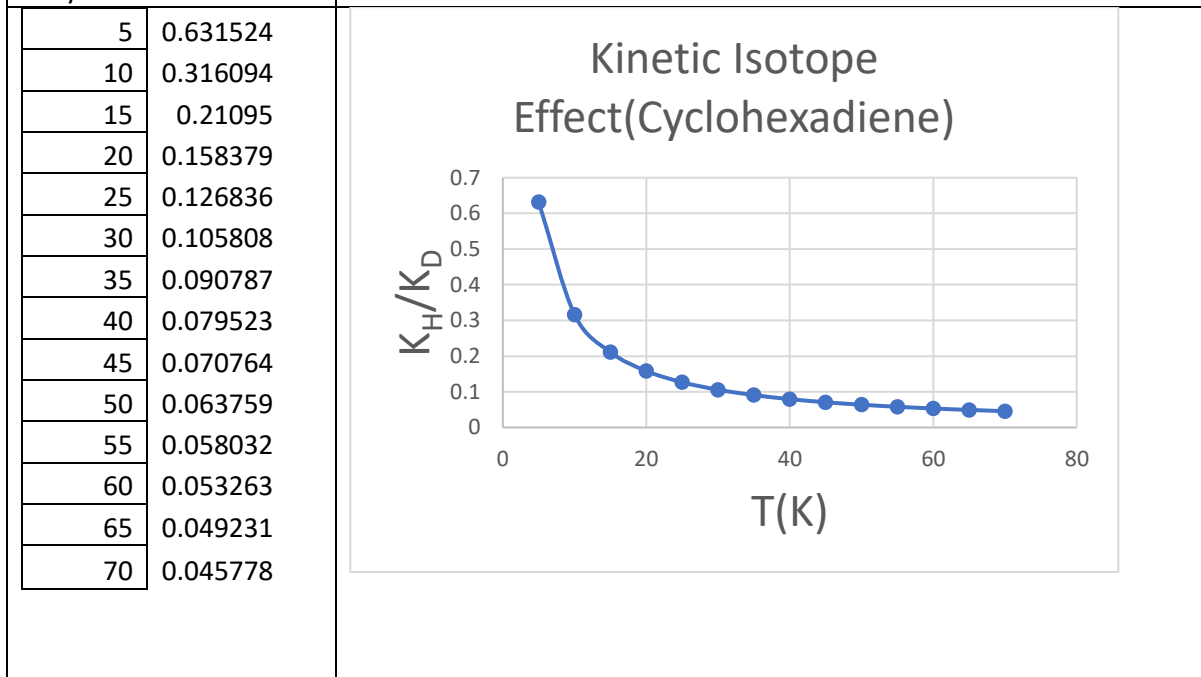
<i>Table 4</i> The isotopic substitution based rate constants K_H/K_D calculated using		
$\frac{k_H}{k_D} = e^{\frac{hc(1-\sqrt{1/2})\bar{\nu}_H}{KT}}$		
H-abstraction reactions with radicals		
1	$\text{CH}_3 + \text{CH}_3\text{CN} \rightarrow \text{CH}_4 + \text{CH}_2\text{CN}$	3.01
2	$\text{CH}_3 + \text{CH}_3\text{NC} \rightarrow \text{CH}_4 + \text{CH}_2\text{NC}$	5.82
3	$\text{CH}_3\text{OH} + \text{OH} \rightarrow \text{CH}_2\text{OH} + \text{H}_2\text{O}$	5.21
4	$\text{CH}_3\text{OH} + \text{CH}_3 \rightarrow \text{CH}_4 + \text{CH}_2\text{OH}$	2.99

K_H / K_D vs Temp(K) Manual Calculations		<i>Table 5.1</i> Manual Calculations	
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic isotope effect(Pentadiene)</p>	
80	57.06609		
100	25.41572		
120	14.82241		
140	10.08427		
160	7.55421		
180	6.0341		
200	5.041401		
220	4.35194		
240	3.849988		
260	3.470756		
280	3.175575		
300	2.940137		
320	2.748492		
340	2.589795		
360	2.45644		
K_H / K_D vs Temp(K) Polyrate Calculations			
Temp(K)	K_H / K_D	<p style="text-align: center;">Kinetic Isotope Effect(Pentadiene)</p>	
5	0.968209		
10	0.983311		
15	0.9884		
20	0.990966		
25	0.992535		
30	0.993615		
35	0.994417		
40	0.995046		
45	0.995557		
50	0.995982		
55	0.996343		
60	0.996653		
65	0.996923		
70	0.997162		

Table 5.2 Manual Calculations



K_H / K_D vs Temp(K)
Polyrate Calculations



K_H / K_D vs Temp(K) Manual Calculations		Table 5.3 Manual Calculations	
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic isotope effect(Indene)</p>	
80	24.12393		
100	12.76317		
120	8.348954		
140	6.165529		
160	4.911612		
180	4.115488		
200	3.572558		
220	3.18206		
240	2.889456		
260	2.662985		
280	2.483048		
300	2.336968		
320	2.216216		
340	2.114861		
360	2.028667		
K_H / K_D vs Temp(K) Polyrate Calculations			
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic Isotope Effect(Indene)</p>	
5	2.314249		
10	1.521174		
15	1.32262		
20	1.233284		
25	1.182606		
30	1.149983		
35	1.127235		
40	1.110472		
45	1.097611		
50	1.087433		
55	1.079179		
60	1.072353		
65	1.066613		
70	1.06172		

K_H / K_D vs Temp(K) Manual Calculations		Table 5.4 Manual Calculations	
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic isotope effect(Phenanthrene)</p>	
80	35.38407		
100	17.33989		
120	10.77801		
140	7.674199		
160	5.948451		
180	4.879317		
200	4.164119		
220	3.657656		
240	3.282988		
260	2.9961		
280	2.770234		
300	2.588305		
320	2.438945		
340	2.31433		
360	2.208918		
K_H / K_D vs Temp(K) Polyrate Calculations			
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic Isotope Effect(Phenanthrecene)</p>	
5	0.817373		
10	0.904135		
15	0.935071		
20	0.950995		
25	0.960772		
30	0.967428		
35	0.972268		
40	0.975946		
45	0.978834		
50	0.981157		
55	0.983064		
60	0.984655		
65	0.986001		
70	0.987154		

K_H / K_D vs Temp(K) Manual Calculations		Table 5.5 Manual Calculations	
Temp(K)	Kh/Kd	<p>Kinetic isotope effect(Pyran)</p>	
80	67.4083		
100	29.03827		
120	16.56312		
140	11.09121		
160	8.210256		
180	6.497728		
200	5.388717		
220	4.623668		
240	4.069782		
260	3.653264		
280	3.330347		
300	3.073668		
320	2.865354		
340	2.693305		
360	2.549064		
K_H / K_D vs Temp(K) Polyrate Calculations			
		<p>Kinetic Isotope Effect(Pyran)</p>	
5	0.792855		
10	0.89208		
15	0.927842		
20	0.946257		
25	0.957481		
30	0.965037		
35	0.970471		
40	0.974567		
45	0.977764		
50	0.98033		
55	0.982435		
60	0.984193		
65	0.985684		
70	0.986964		

K_H / K_D vs Temp(K) Manual Calculations		Table 5.6 Manual Calculations	
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic isotope effect(Thiopyran)</p>	
80	85.71177		
100	35.19106		
120	19.43988		
140	12.72315		
160	9.258065		
180	7.229847		
200	5.932206		
220	5.045728		
240	4.409068		
260	3.933523		
280	3.566952		
300	3.277008		
320	3.042707		
340	2.849923		
360	2.688837		
K_H / K_D vs Temp(K) Polyrate Calculations			
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic Isotope Effect(Thiopyran)</p>	
5	0.855683		
10	0.926323		
15	0.951143		
20	0.963801		
25	0.971476		
30	0.976628		
35	0.980324		
40	0.983105		
45	0.985275		
50	0.987016		
55	0.988444		
60	0.989637		
65	0.990651		
70	0.991522		

K_H / K_D vs Temp(K) Manual Calculations		Table 5.7 Manual Calculations			
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic Isotope Effect(Dihydropyridine)</p>			
80	85.71177				
100	35.19106				
120	19.43988				
140	12.72315				
160	9.258065				
180	7.229847				
200	5.932206				
220	5.045728				
240	4.409068				
260	3.933523				
280	3.566952				
300	3.277008				
320	3.042707				
340	2.849923				
360	2.688837				
K_H / K_D vs Temp(K) Polyrate Calculations				Polyrate Calculations	
Temp(K)	Kh/Kd			<p style="text-align: center;">Kinetic Isotope Effect(Dihydropyridine)</p>	
5	0.711683				
10	0.843624				
15	0.892832				
20	0.918503				
25	0.93426				
30	0.944921				
35	0.952624				
40	0.958463				
45	0.963052				
50	0.966765				
55	0.969838				
60	0.972431				
65	0.974652				
70	0.976579				

K_H / K_D vs Temp(K) Manual Calculations		Table 5.8 Manual Calculations	
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic isotope effect(Methyl Isocynaide)</p>	
80	740.2195		
100	197.4642		
120	81.82896		
140	43.61487		
160	27.20698		
180	18.84826		
200	14.0522		
220	11.05106		
240	9.045936		
260	7.63625		
280	6.604156		
300	5.823215		
320	5.216031		
340	4.733078		
360	4.341459		
K_H / K_D vs Temp(K) Polyrate Calculations			
Temp(K)	Kh/Kd	<p style="text-align: center;">Kinetic isotope effect(Methanol+OH)</p>	
80	740.2195		
100	197.4642		
120	81.82896		
140	43.61487		
160	27.20698		
180	18.84826		
200	14.0522		
220	11.05106		
240	9.045936		
260	7.63625		
280	6.604156		
300	5.823215		
320	5.216031		
340	4.733078		
360	4.341459		

K_H / K_D vs Temp(K) Manual Calculations		Table 5.9 Manual Calculations	
Temp(K)	K_H/K_D	<p style="text-align: center;">Kinetic isotope effect(Methanol+CH3)</p> <p style="text-align: center;">K_H/K_D</p> <p style="text-align: center;">Temp(K)</p>	
80	61.26733		
100	26.90191		
120	15.54125		
140	10.50204		
160	7.827345		
180	6.227647		
200	5.186706		
220	4.465822		
240	3.942239		
260	3.547453		
280	3.240685		
300	2.996363		
320	2.797739		
340	2.633446		
360	2.495525		
K_H / K_D vs Temp(K) Polyrate Calculations			
Temp(K)	K_H/K_D	<p style="text-align: center;">Kinetic isotope effect(Methyl Cynaide +CH3)</p> <p style="text-align: center;">K_H/K_D</p> <p style="text-align: center;">Temp(K)</p>	
80	62.87839		
100	27.46636		
120	15.81251		
140	10.65897		
160	7.92959		
180	6.299905		
200	5.240836		
220	4.508172		
240	3.976495		
260	3.575897		
280	3.264807		
300	3.017174		
320	2.815953		
340	2.649579		
360	2.509961		

Conclusions

The Gaussian 09W program package has been explored to optimize the geometry of the molecules using Density Functional Theory ({B3LYP/6-31G(d,p)) functional}. Transition state was generated using Gaussian 09 W for various chemical reactions. The transition state calculations are performed for 1,5 Hydrogen shift reactions and Hydrogen abstraction reactions using free radicals.

B3LYP functional succeeded reasonably well in describing [1,5] H-Shift reactions for Cyclohexadiene, Indene, Phenanthracene. The results obtained in doing DFT calculations with B3LYP functional didn't match with experimental data for [1,5] H-Shifts with increase in number of rings and for radical based reactions..

POLYRATE is understood and explored in minimum possible way. With the limited knowledge that we had on polyrate and in the given time line the expected trend in the results for radical reactions could not be performed. Later, when the validity of polyrate program for H-abstraction reactions was checked, it is realized that it failed for B3LYP functional and to get valid results one need to use MPWB1K functional that is optimized against kinetic database.

Subsequently K_H/K_D ratio was computed manually at various temperatures (273K to 318K) and it showed the expected results for all reactions.

The temperature dependence of the KIE presents the more robust and predictive probe for understanding the physical parameters that control H-tunnelling. During H tunneling in proton-transfer reactions the tunneling parameter depends on population distribution along the reaction coordinate. Tunneling probability distribution factor is

$$Q \left(= \frac{e^\alpha}{\beta - \alpha} (\beta e^{-\alpha} - \alpha e^{-\beta}) ; \alpha = \frac{E}{RT} ; \beta = \frac{2a\pi^2(2mE)^{1/2}}{h} \right) \text{ in Arrhenius equation } k = QA e^{-E/RT}$$

and is a function of donor acceptor distance and the mass of the transferred particle. On calculation of KIEs (K_H/K_D ratio) many factors that are not isotopically sensitive drop from the equation. If

the probability distribution of reaction coordinate is not mass-sensitive, then the distribution can fit KIEs with little to no temperature dependence. But in case the tunneling probability is mass dependent the K_H/K_D ratio for the reactions follows a single exponential relationship with temperature. The tunneling parameters also depend on the flexibility and rigidity of the reacting system. For the reactions studied the data reveals with decreasing temperature the ratio K_H/K_D increases. This indicates tunneling is prevalent at low temperatures and is temperature dependent.

A proper understanding of the mechanism of these reactions can take the concept a long way where it can be used for understanding of reactions useful for societal benefits and environment.

References

- 1) David Ley et. al Organic and Biomolecular chemistry, 2012, 10,3781-3790.
- 2) M. G. Evans and M. Polanyi, Trans. Faraday Soc., 1935, 31, 875–894.
- 3) C. G. Swain, E. C. Stivers, J. F. Reuwer and L. J. Schaad, J. Am. Chem.Soc., 1958, 80, 5885–5893.
- 4) The Tunnel Effect in Chemistry; Bell, R. P.;Chapman and Hall:New York, 1980.
- 5) R. P Bell Trans. Faraday.Soc.,1971, 67,1995-2003.
- 6) Frisch, M. J., G.W. Trucks , H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman , J. A., Jr .Montgomery ,T.Vreven , K. N.Kudin , J. C. Burant , J. M Millam , S. S Iyengar , J. Tomasi , V. Barone , B. Mennucci , M. Cossi , G. Scalmani , N. Rega ,G. A. Petersson , H. Nakatsuji , M. Hada , M. Ehara , K.Toyota , R. Fukuda , J. Hasegawa , M. Ishida, T.Nakajima,Y .Honda ,O. Kitao, H. Nakai , M. Klene , X. Li , J. E Knox, H.P. Hratchian , J. B. Cross,V. Bakken, C. Adamo, J. Jaramillo , R. Gomperts, R. E. Stratmann , O. Yazyev, A. J. Austin, R. Cammi , C. Pomelli , J. W Ochterski , P. Y Ayala, K. Morokuma, G.A.Voth,P.Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas , D. K. Malick , A. D. Rabuck , K. Raghavachari,J. B. Foresman, J. V. Ortiz, Q.Cui , A. G. Baboul, S.Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko , P. Piskorz ,I. Komaromi, R. L. Martin, D. J Fox, T.Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara , M. Challacombe,P.M.W Gill, B. Johnson, W. Chen, M. W.Wong, C.Gonzalez, J. A. Pople, GAUSSIAN 03, Revision E.01; Gaussian, Wallingford CT, 2004.
- 7) J.B. Foresman, in: E. Frisch (1996) *Exploring Chemistry with Electronic Structure Methods: a Guide to Using Gaussian*, Pittsburg, PA.
- 8) Can aromaticity trigger thermal [1,5]-halogen shift towards the forbidden antarafacial mode?: A density functional case study P. Kalpana | L. Akilandeswari
- 9) Quantum Mechanical Tunneling in Free Radical Reactions; V. Malatesta, K. U. Ingold, and C. Chatgililoglu pp 541 in 1981_Book_Fast Reactions In EnergeticSystem.pdf ; DOI: 10.1007/978-94-009-8511-7
- 10) Bradford B.Wright , V.P.Senthilnathan , Matthew S.Platz , C.W. McCurdyJr. Tetrahedron Letters, Volume 23, Issue 8, 1982, Pages 833-836; [https://doi.org/10.1016/S0040-4039\(00\)86961-0](https://doi.org/10.1016/S0040-4039(00)86961-0)

- 11) Kinetic Isotope Effects in Free Radical Chemistry. Kenneth George Kneipp Louisiana State University and Agricultural & Mechanical College Ph D thesis, 1971.
- 12) Control of Kinetics and Thermodynamics of [1,5]-Shifts by Aromaticity: A View through the Prism of Marcus Theory; Igor V. Alabugin , Mariappan Manoharan, Boris Breiner,†and Frederick D. Lewis. Journal of American Chemical Society, 2003
DOI: 10.1021/ja035729x
- 13) Hydrogen Donor–Acceptor Fluctuations from Kinetic Isotope Effects:
A Phenomenological Model, Daniel Roston, Christopher M. Cheatum, and Amnon Kohen
- 14) J. Zheng, J. L. Bao, R. Meana-Pañeda, S. Zhang, B. J. Lynch, J. C. Corchado, Y.-Y. Chuang, P. L. Fast, W.-P. Hu, Y.-P. Liu, G. C. Lynch, K. A. Nguyen, C. F. Jackels, A. Fernandez Ramos, B. A. Ellingson, V. S. Melissas, J. Villà, I. Rossi, E. L. Coitiño, J. Pu, T. V. Albu, A. Ratkiewicz, R. Steckler, B. C. Garrett, A. D. Isaacson, and D. G. Truhlar, *Poltrate*-version 2017-C (University of Minnesota, Minneapolis, MN, 2017).
- 15) Benchmarking of DFT functionals for the kinetics and mechanisms of atmospheric addition reactions of OH radicals with phenyl and substituted phenyl-based organic pollutants Fangfang Ma | Hong-Bin Xie | Jingwen Chen Received: 6 July 2017 | Revised: 1 October 2017 | Accepted: 20 October 2017 DOI: 10.1002/qua.25533

Objectives met and concepts learnt during the tenure of the project

1) The Gaussian 09W program package has been explored to optimize the geometry of the molecules using Density Functional Theory. The computed results concerning molecular geometric structure in ground state are obtained using (B3LYP/6-31G(d,p)).

2) Transition state for H-Shift reactions and H-abstraction reactions with OH radicals are calculated using Gaussian 09 W.

3) POLYRATE is understood and explored in minimum possible way. With the limited knowledge that we had on polyrate and in the given time line the expected trend in the results for radical reactions could not be performed. Repetition of kinetic studies of Hydrogen shift reactions at various temperatures (273K to 318K) is performed using polyrate K_H/K_D ratio is evaluated.

4) K_H/K_D ratio was computed manually Using R P Bell equation at various temperatures (273K to 318K) and the results are in accordance with experimental data for H- shift reactions.

5) The temperature dependence of the KIE(K_H/K_D ratio) presents the more robust and predictive probe for understanding the physical parameters that control H-tunnelling. During H tunneling reactions it is learnt that the tunnelling parameter depends on population distribution along the reaction coordinate i.e donor acceptor distance, the mass of the transferred particle (H/D) and on the flexibility and rigidity of the reacting system. The reactions follows a single exponential relationship with temperature as tunnelling factor dependent on mass of the particle.

6) It has wide applications in quantum biology because tunnelling plays a role in many biochemical redox reactions (photosynthesis, cellular respiration) as well as enzymatic catalysis. Proton tunnelling is a key factor in spontaneous DNA mutation also. So, if we can control these mutations which occur mainly due to proton tunnelling, we can also control DNA repair mechanisms. A proper understanding of the mechanism of these reactions can take the concept a long way where it can be used for understanding of reactions useful for societal benefits and environment.