

Effect of Vibrational Strong Coupling on Concerted Reactions

Athul Vijay V C

*A dissertation submitted for the partial fulfilment of
BS-MS dual degree in Science*



Department of Chemical Sciences
Indian Institute of Science Education and Research Mohali
May 2020

Certificate of Examination

This is to certify that the dissertation titled “**Effect of Vibrational Strong Coupling on Concerted Reactions**” submitted by **Mr. Athul Vijay V C** (Reg. No. MS15117) for the partial fulfilment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Dr. P. Balanarayan

Assistant Professor

Dr. Sugumar Venkataramani

Assistant Professor

Dr. Jino George

Assistant Professor

(Supervisor)

Dated: May 27, 2020

Declaration

The work presented in this dissertation has been carried out by me under the guidance of **Dr. Jino George** at the Indian Institute of Science Education and Research Mohali.

This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgement of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Athul Vijay V C

(MS15117)

Dated: May 27, 2020

In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. Jino George
(Supervisor)

Acknowledgement

I would like to thank my guide **Dr. Jino George** for his consistent guidance and advices during the entire project. Without his suggestions and help this dissertation would have been impossible.

I would like to thank my thesis committee members Dr. P. Balanarayan and Dr. Sugumar Venkataramani for their valuable suggestions and comments to accomplish the work.

I would like to thank Mr.Jaibir for his valuable suggestions and help throughout the project

I would also like to extend my thanks to other lab members Jyoti Lather, Pooja Bhatt, Akhila Kadyan , Kuljeet Kaur, Jhuma, Chithra and Thabassum for their suggestions and support.

I would like to acknowledge DCS facility and IISER Mohali for all the facilities

List of Figures

Figure 1.1 a) Formation of hybrid light matter states (P+ and P-) when a two-level atom cavity mode enters strong coupling regime. b) Transmission of an empty cavity mode and transmission spectrum of polaritonic states

Figure 1.2 a) Structure of a F-P cavity consisting of two parallel mirrors M1 and M2 with reflectance R1 and R2 respectively separated with a length L and surrounding a cavity medium of refractive index n b) Transmission of a F-P cavity with FSR equal to $\frac{c}{2nL}$, Full width at half maximum is represented as $\Delta\nu$

Figure 1.3 Vibrational Strong Coupling. Formation of hybrid light matter state due to coupling between ground state molecular vibration cavity mode

Figure 1.4 Potential energy surface of a concerted reaction and that of hypothetical states originated from vibrational strong coupling

Figure 2.1 a) Reaction coordinate diagram of a three step reaction with two intermediates and three high energy transition state b) Reaction coordinate diagram of a single step reaction left most starting point shows reactants and far right indicates products

Figure 2.2 π molecular orbitals formed from P orbitals on sp^2 hybridised carbons in ethylene and butadiene

Figure 2.3 conrotatory and disrotatory processes in electrocyclic reactions

Figure 2.4 Cyclisation of Citronellal giving four diastereoisomers as products

Figure 2.5 Lewis acid catalysed carbonyl -ene reaction. stereochemistry comes from an all-chair arrangement in the conformation of the transition state. The methyl group will adopt an equatorial position in this conformation, fixing the way the other bonds are formed

Figure 2.6 Bismuth triflate catalysed citronellal cyclisation, a scheme of reaction which yields isopulegol and neo-isopulegol with 80:20 ratio respectively

Figure 2.7 Schematic representation of a Fabry-Perot cavity and the original picture of cavity used to conduct the experiment

Figure 2.8 Combined IR spectra of Pure Citronellal and Citronellal + Catalyst (without Solvent)

Figure 2.9 a) Combined IR data with time b) Zoomed spectra of peak at 2720cm^{-1} c) and d) first order kinetics plot to find out the reaction rate

Figure 2.10 First order kinetics plots to find out the reaction rate with 0.02 % of catalyst

Figure 2.11 Combined spectra of cavity and non-cavity data at zero minute

Figure 2.12 a) Cavity data of 0.02 % catalyst + cyclohexanone + citronellal reaction observed for 750seconds b) Zoomed region around 2720 cm^{-1} c) Strong coupled region of carbonyl peak

Figure 2.13 Reaction rate calculation using FSR shift method for ON resonance cavity.

Figure 2.14 Combined first order initial rate calculation plots of cell and cavity data

List of Tables

Table 2.1 Frequency shift of the $\nu_{C=O}$ absorption band of CNAL in CNAL-solvent mixtures

Table 2.2 Citronellal cyclisation with different solvents using bismuth triflate as catalyst and selectivity between the products

Abbreviations

CNAL	Citronellal
CHX	Cyclohexanone
TOL	Toluene
EtOH	Ethanol
CLF	Chloroform
ACN	Acetonitrile
2-PrOH	2-Propanol
FWHM	Full Width at Half Maximum
FMO	Frontier Molecular Orbitals
HOMO	Highest Occupied Molecular Orbital
LUMO	Lowest Unoccupied Molecular Orbital
VSC	Vibrational Strong Coupling
FSR	Free Spectral Region
FPC	Fabry-Perot Cavity

Content

1. Introduction

- 1.1 History and Progress
- 1.2 Theoretical Perspectives
 - 1.2.1 Vacuum fluctuations
 - 1.2.2 Interaction between light and Matter
 - 1.2.3 Quantum description of strong coupling regime
 - 1.2.4 Strong Coupling Limit
- 1.3 Experimental methods to obtain strong coupling regime
- 1.4 Vibrational Strong Coupling

2. Effect of Vibrational Strong Coupling in Concerted Reactions

- 2.1 Introduction
 - 2.1.2 System Under Study: Cyclisation of Citronellal to Isopulegol
- 2.2 Experimental Methods
- 2.3 Results and Discussions
 - 2.3.1 Kinetics under Non-cavity conditions
 - 2.3.2 Kinetics under Cavity Conditions
- 2.4 Conclusions

3. Bibliography

Abstract

Formation of new hybrid light matter states-called as polaritonic states-by interaction of molecular transitions and resonant optical cavity mode is a novel research field in the area of physical chemistry. Strong coupling between molecular transition and cavity mode gives us the possibility for altering the physical and chemical properties of a system. It can also apply in the ground state molecular vibrations which is called as vibrational strong coupling that helps to perturb a given bond and thus changes the rate of a reaction. In the current thesis we focus on understanding the effect of vibrational strong coupling on concerted reactions. For that purpose, we choose cyclisation of citronellal to isopulegol as a model reaction under study. Isopulegol is the starting material for the production of menthol, which is a commercially important product. In the current thesis, we try to follow a concerted reaction by either directly coupling the reactant state or co-operatively coupling a solvent in which their vibrational energy overlaps. Preliminary studies suggest that the reaction rate get deaccelerated by approximately 1.5 times compared to the non-cavity conditions. These studies prove that how VSC can influence rate of a reaction that varies with nature of the reactant and the transition state as their free energy variation are purely depend upon the coupling conditions. Further studies are required to understand the effect of VSC on controlling the potential energy surface of a chemical reaction.

CHAPTER 1

INTRODUCTION

Cavity quantum electrodynamics (Cavity QED) is related to the study of simplest and non-trivial model of light-matter interaction in a reflective cavity where quantum nature of light (photon) is significant. To obtain that, an atom was placed in between two mirrors which confine some electromagnetic field and atom is then coupled to the light. It belongs to a comparatively new field of research in atomic physics and quantum optics. Einstein demonstrated that spontaneous emission as an inherent property of matter. However in 1989, Serge Haroche and Daniel Kleppner overlooked the fact that spontaneous emission is a property of atom-vacuum system and not of an isolated atom. Their experiments showed that when excited atom is placed in cavities or mirrors spontaneous emission can be greatly suppressed or enhanced.

Cavity QED has started by considerations about spontaneous emission of an atomic excited state in the presence of boundaries.^[1] Two main types of regimes (weak and strong coupling) forms depending upon the ratio of light-matter coupling strength per boson and the irreversible losses from both emitter and bosonic mode. In the weak coupling regime losses dominates and lifetime gets modified, but in the case of strong coupling regime coupling dominates the losses.^[2] In this chapter we will discuss the historical background and theoretical perspectives of light matter interaction and molecular strong coupling.

1.1 History and Progress

In 1946 Edward Purcell observed that due to nuclear magnetic moments spontaneous emission rate in a resonant structure was enhanced. It was one of the pioneer experiment related to Cavity QED which considered spontaneous emission of atom with

the presence of boundaries.^[3] In 1975 V.A. Yakovlev et.al experimentally demonstrated the splitting of surface plasmon polaritons due to resonance between thin surface film oscillations and theoretically proved that later. In 1983 self-induced Rabi oscillations were reported when electromagnetic field was coupled with two level Rydberg atoms inside an optical cavity by Haroche et al. In 1985 one atom maser experiment by H.Walther on Rydberg atoms showed the exchange of photons between single mode of superconducting cavity with single atoms. In 1989 normal mode splitting and linewidth averaging for a collection of two-state atoms was observed in optical cavity by M. G. Raizen and et al.^[4] After three years, strong coupling between exciton and photon in semiconductor microcavity was observed by C.Weishbuch.^[5] In 2011, reversible switching from strong coupling to weak coupling regime was observed. In the next year Hutchison and team observed that rate of a chemical reaction can be modified by coupling the electronic transitions with vacuum field. Later they also found out that it is not limited to electronic transitions and ground state molecular vibrations were coupled with vacuum fields and that resulted in the formation of vibro-polaritonic states. In 2015 experiments related to coupling of ground state vibrations in liquid state were also conducted. Later catalytic effect of co-operative vibrational strong coupling of reactant and solvent molecules were also observed.

1.2 Theoretical Perspectives

Two harmonic oscillators will behave independently if they are uncoupled. When they are in resonance, coupling between them is strong enough and they will start periodically exchanging energy and the system will behave as one single entity. In the strong coupling regime, they develop two new normal modes and the energy separation between the modes is called as normal mode splitting.

1.2.1 Vacuum Fluctuations

We have already discussed what strong coupling means from a classical perspective and now we can look in to the quantum description of strong coupling. Classical description is not sufficient to describe all signatures of strong coupling regime due to presence of vacuum field. Vacuum fluctuations or zero-point energy is the ground state energy of the quantized electromagnetic field. In 1916 Nernst observed that vacuum fluctuations exist in

a field mode and it was confirmed by quantum theory of electromagnetic field. Strength of vacuum electric field in an optical cavity is given by

$$\mathcal{E}_{vac} = \sqrt{\frac{\hbar\omega_c}{2\epsilon_0 v}}$$

ω_c is cavity frequency and ϵ_0 is vacuum permittivity and v is the mode volume of cavity.

1.2.2 Interaction between light and Matter

Coupling is described by the total transition dipole moment of the molecule and a uniform electric field. All of the molecules are not coupled simultaneously because molecules are oriented randomly. Thomson–Lorentz model of the atom represents an atomic ensemble as a collection of oscillators. Electromagnetic field can also be considered as a collection of independent oscillators. Transition dipole moment is the key parameter which determines interaction between light and matter using dipole-dipole interaction. The coupling (V) between light and matter is described by a dipolar coupling term;

$$V = -\vec{d} \cdot \vec{\epsilon}$$

where ϵ is the electric field operator and d is the transition dipole moment. A change in electromagnetic density of states can (DOS) can drastically change the rate of spontaneous emission is known as Purcell Effect. In 1987 D. J. Heinzen observed experimental demonstration of Purcell effect at optical frequencies. When a molecule emits inside a cavity, those photons will remain inside the cavity because it gets reflected by the mirrors. So, the chance of reabsorption by molecule increases and if that is higher than the probability of photon leakage that system will enter into strong coupling regime.

1.2.3 Quantum description of strong coupling regime

Simple model of cavity QED consists of two-level emitter and a single mode of electromagnetic field. Jaynes-Cummings Hamiltonian consider this system as sum of molecule, electric field and molecule-field interaction.

$$\widehat{H}_{jc} = \widehat{H}_{mol} + \widehat{H}_{cav} + \widehat{H}_{int}$$

This model can be extended to N-molecules by taking limit of large number of molecules and small number of photons. So, these collection of two-level molecular system then will act as a giant quantum oscillator.

$$\widehat{H} \cong \hbar\omega \left(-\frac{N}{2} + \hat{b}^\dagger \hat{b} \right) + \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar g (\hat{a}^\dagger \hat{b} + \hat{a} \hat{b}^\dagger)$$

Where $g = g_0\sqrt{N}$ is the collective coupling and \hat{a}, \hat{a}^\dagger are creation and annihilation operator for field mode and \hat{b} is the bosonic operator. It shows that light matter coupling strength is increased by a factor \sqrt{N} . When this Hamiltonian is applied through Hopfield–Bogoliubov method gives two new hybrid states of light and matter which is called

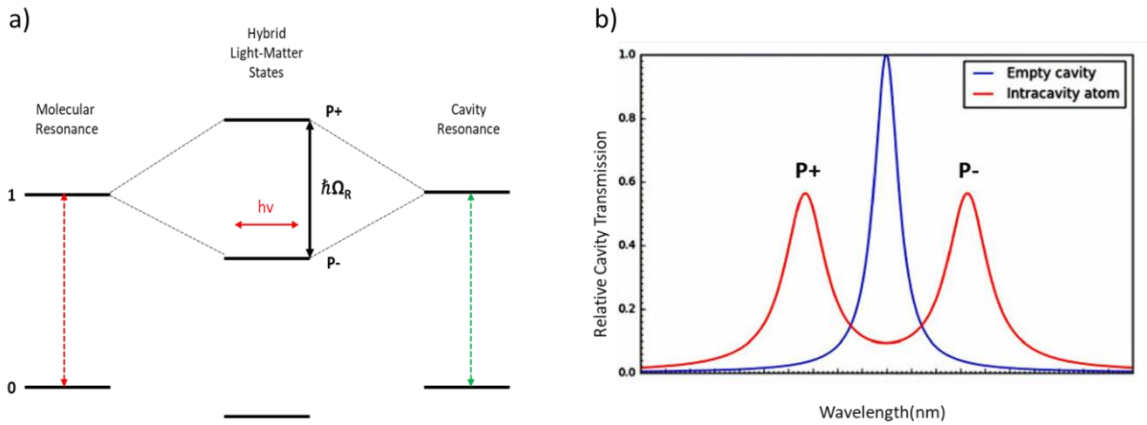


Figure 1.1 a) Formation of hybrid light matter states (P+ and P-) when a two-level atom cavity mode enters strong coupling regime. **b)** Transmission of an empty cavity mode and transmission spectrum of polaritonic states (Ref 6)

as Polaritons or Polaritonic States:

$$|P + \rangle = c_{11}|e\rangle_m|0\rangle_c + c_{12}|g\rangle_m|1\rangle_c$$

$$|P - \rangle = c_{22}|e\rangle_m|0\rangle_c + c_{21}|g\rangle_m|1\rangle_c$$

Where $|g\rangle$ and $|e\rangle$ are ground and excited state of molecule respectively. The phenomenon which leads to the formation of these polaritonic states is known as light-matter strong coupling is shown in figure 1. Energy difference between P+ and P- is called as vacuum Rabi Splitting. It can be expressed as

$$h\Omega_R = 2V_n = 2\vec{d} \cdot \vec{\epsilon} = \sqrt{\frac{h\omega}{2\epsilon_0 v}} X \sqrt{n_{photons} + 1}$$

1.2.4 Strong Coupling Limit

A system is said to be in strong coupling regime if $2g > \frac{(\gamma+\kappa)}{2}$ where g is the coupling strength and γ is the non-resonant decay of molecule and κ is the photon decay rate of cavity. Also they can be related to linewidths of molecular absorption and cavity mode respectively. The above equation shows that light matter interaction is faster than dissipation process. So, the molecule can reabsorb the emitted photon multiple times before it get lost. Conversely if $g \ll [\gamma, \kappa]$ system is said to be in weak coupling regime. For the transition between weak and strong coupling occurs the splitting Ω_R must be greater than FWHM of cavity mode and molecular absorption.

1.3 Experimental methods to obtain strong coupling regime

Rabi splitting is achieved by coupling molecular ensemble in optical cavities called as Fabry-Perot (F-P) cavities. It consists of two plane parallel mirror separated by a length L as shown in figure 1.2.

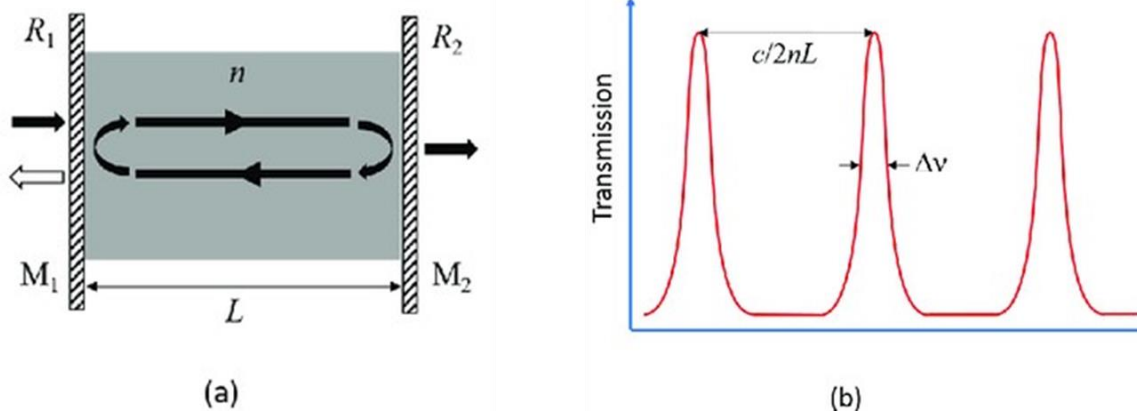


Figure 1.2 a) Structure of a F-P cavity consisting of two parallel mirrors M1 and M2 with reflectance R1 and R2 respectively separated with a length L and surrounding a cavity medium of refractive index n **b)** Transmission of a F-P cavity with FSR equal to $\frac{c}{2nL}$, Full width at half maximum is represented as $\Delta\nu$ (Ref 7)

Then the frequency difference between two consecutive mode, also known as free spectral region (FSR) is given by;

$$\nu = \frac{c}{2nL}$$

where n is the refractive index and L is the distance separated between two mirrors (normally in micrometres). FSR can be calculated from the difference in frequency between adjacent modes measured at peak maximum.

1.4 Vibrational Strong Coupling

Strong light matter coupling gives us the possibility for changing the chemical and physical properties of a system. It was observed that a chemical reaction can be controlled by coupling the electronic state of a molecule. There are studies conducted to find out this

modification in photochemical isomerisation reaction rate^[6], enhancement in charge conductivity, light harvesting complexes^[26], work function of organic molecules^[11] etc.

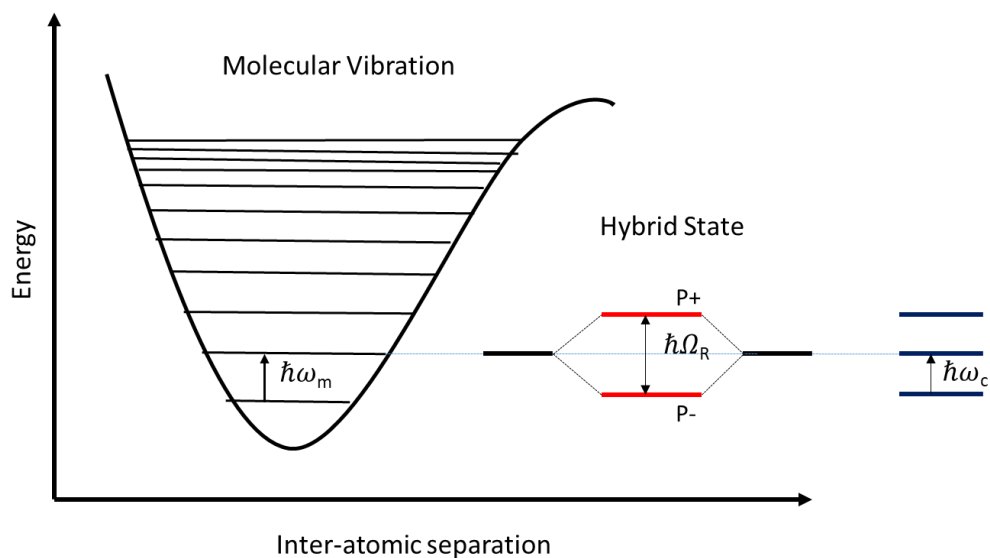


Figure 1.3 Vibrational Strong Coupling| Formation of hybrid light matter state due to coupling between ground state molecular vibration and a cavity mode.

Light matter strong coupling is not limited to electronic transition it can also apply in the ground state molecular vibrations. In figure 1.3 it shows formation of hybridised vibropolaritonic states when the ground state molecular vibrational mode is coupled with optical cavity mode.

In a microfluidic cavity the energy of ground state can also alter due to strong coupling with electromagnetic field. As described earlier due to vacuum fluctuations it can be obtained even without applying an external electromagnetic field. Coupling with vibrational transition can be hence used to perturb a given bond and through that a given chemical reaction. Different types of chemical reactions are tested under such condition which includes ester hydrolysis to complex enzymatic reactions. It was observed that the reaction envelope changes depending upon the coupling conditions. Some of the reactions

showing a retardation process, whereas, others show catalysis as shown in figure 1.4. Cooperativity effects with solvents during catalyzing a chemical reactions with cavity conditions are also been studied.

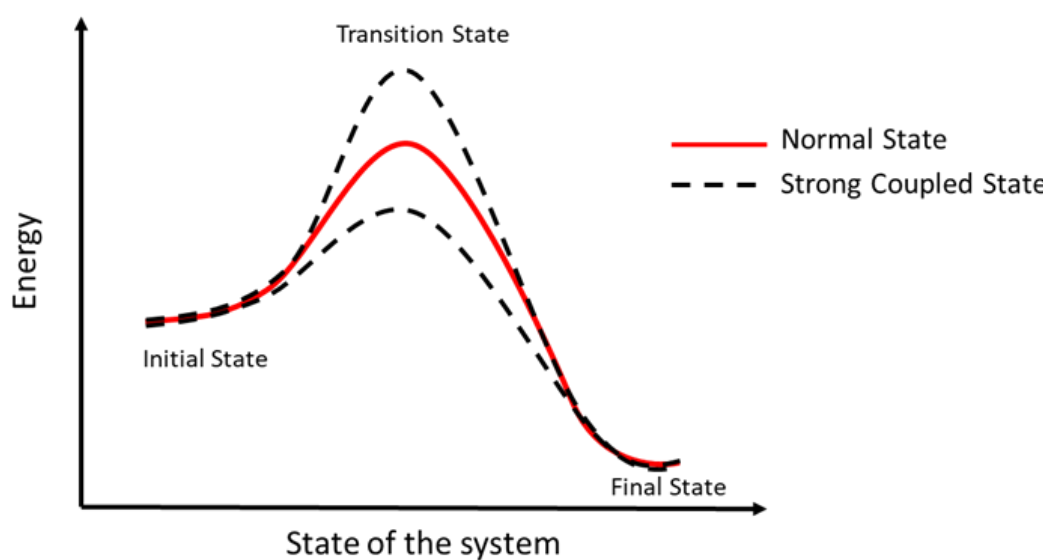


Figure 1.4 Potential energy surface of a concerted reaction and that of hypothetical states originated from vibrational strong coupling.

The actual focus of my thesis work is to consider the influence of frontier molecular orbitals (FMOs) that control concerted processes such as pericyclic reaction which obey the Woodward-Hoffmann rule. After choosing a real example of concerted reaction for experimental studies, I will try to find out the influence of vibrational strong coupling, which can possibly control the symmetry of FMOs, in turn affect the course of the reaction.

CHAPTER 2

2.1 Introduction

Energy-reaction coordinate is a tool for understanding the dynamics of a chemical reaction, which gives information about the actual path taken by reactant (s) when they converted into product (s). During this process the system will have to go through a transition state (TS). Rate of a reaction is depended on the number of molecules that have sufficient energy to overcome the high energy barrier. Rate of a reaction is generally increased by either raising the temperature or by lowering the energy barrier by using a catalyst.

In the figure 2.1a reaction coordinate of a multistep chemical reaction is shown. If a reaction is having multistep it will have many 'hills and valleys' in the reaction coordinate. In the figure2.1a it has two intermediates and three barriers, that indicates it is a three-step process (left side of the diagram is the reactant and right side is the product). A chemical reaction in which all bond breaking and making occurs in one step is called as concerted reaction. In a concerted reaction no other reactive intermediate will be involved.

Most of the organic reactions happens by polar mechanisms in which a bond is forming by two electron transfer between nucleophile to electrophile. Other kinds of reactions will follow radical mechanism in which each of the two reactants will donate one electron each for forming a new bond. Pericyclic reactions are another kind of organic reactions which are less common. A concerted reaction that proceeds through a cyclic transition state is known as pericyclic reaction. In a pericyclic reaction bond breaking and forming occurs

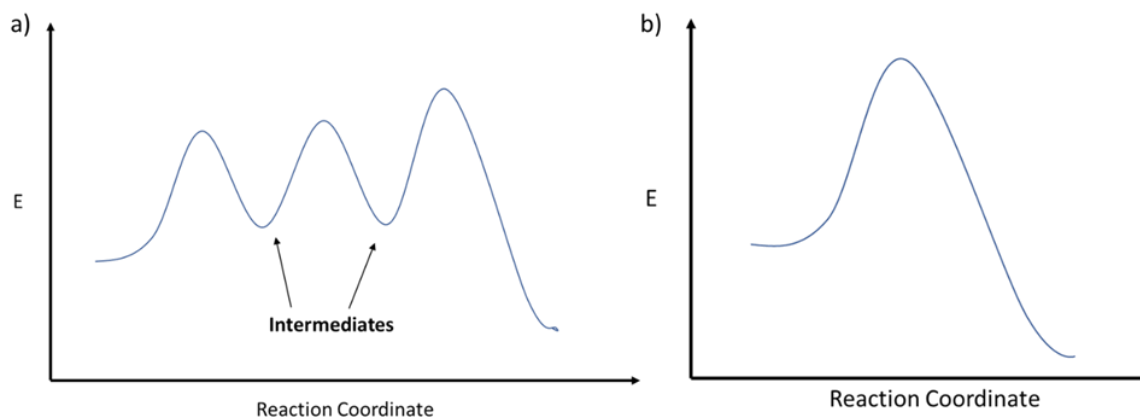


Figure 2.1 a) Reaction coordinate diagram of a three step reaction with two intermediates and three high energy transition state b) Reaction coordinate diagram of a single step reaction left most starting point shows reactants and far right indicates products

simultaneously. Major classifications of pericyclic reactions include electrocyclic ring opening/closing, cycloaddition reactions and sigmatropic rearrangements. Orbital symmetry correlation method by Woodward and Hoffmann is mainly used for analysing a pericyclic reaction.

In accordance with molecular orbital theory, in a conjugated polyene (an acyclic hydrocarbon with alternate C-C and C=C bonds), P orbitals on sp^2 hybridised carbons will interact to form a set of π orbitals. Energies of these newly formed π orbitals will depend upon the number of nodes they have between nuclei. Molecular orbitals with less number of nodes will form bonding orbitals and with more nodes will form anti bonding orbitals. Bonding orbitals will have less energy than P atomic orbitals and antibonding orbitals will have higher energy. π molecular orbitals formed from P orbitals on sp^2 hybridised carbons in ethylene and butadiene is shown in the figure 2.2.

In the mid 1960s, R. B. Woodward and Roald Hoffmann formulated some rules about pericyclic reactions on the basis of their molecular orbital symmetry. According to them pericyclic reactions will take place only if symmetries of molecular orbitals of both reactant and products are same. In a symmetry allowed reaction molecular orbitals of reactants and products will correlate and conversely in the case of a symmetry disallowed reaction. Symmetry disallowed reactions will take place non-concerted or high energy pathways only.

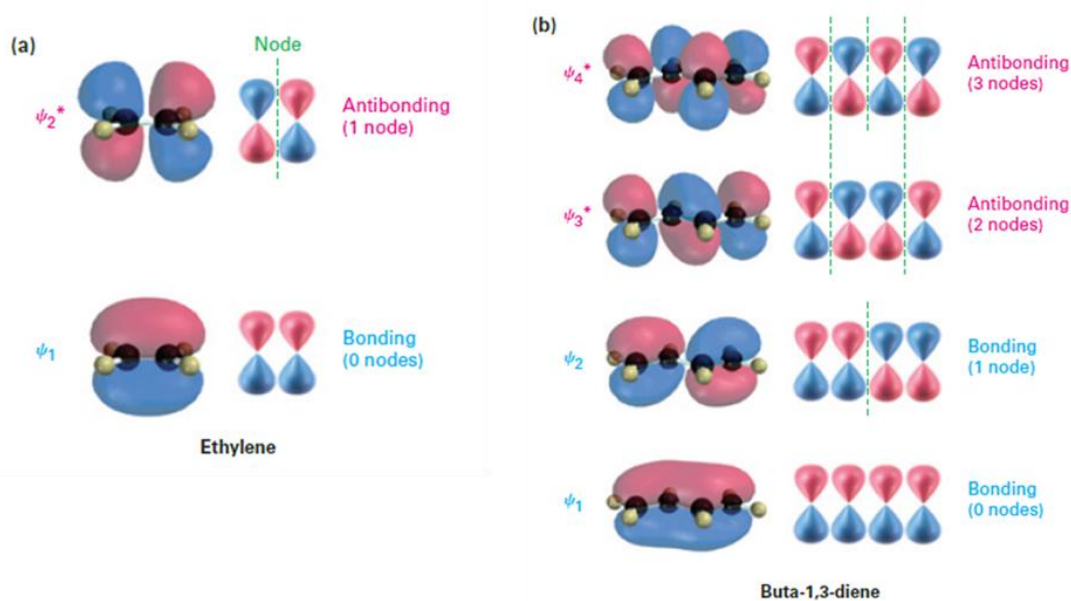


Figure 2.2 π molecular orbitals formed from P orbitals on sp^2 hybridised carbons in ethylene and butadiene (Ref 34)

Electrocyclic reactions come under pericyclic process in which a polyene intramolecularly reacts and forms rings by clipping their ends with temperature or light. During this one π bond will break and another π bond will change its position and forms a new σ bond. In 1965, Woodward–Hoffmann rules were constructed first to explain the stereospecificity in electrocyclic reactions with thermal and photochemical control^[29]. For a bond formation to happen outermost π lobes must rotate so that favorable bonding interaction will be obtained as in figure 2.3.

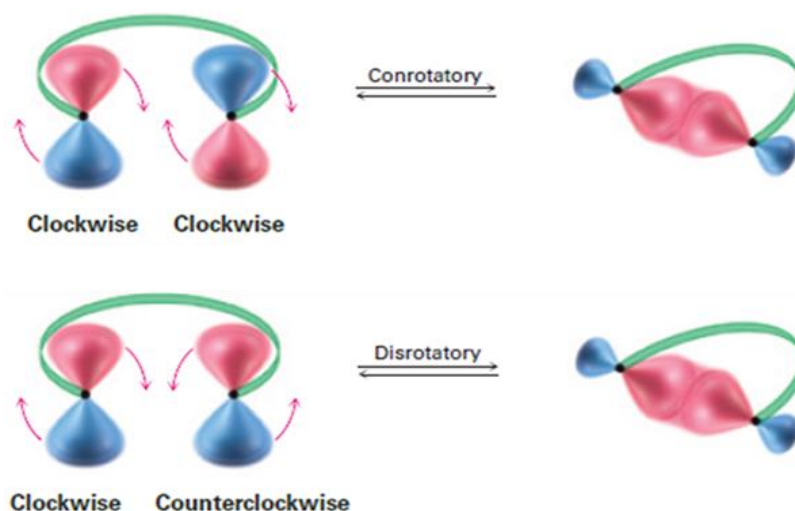


Figure 2.3 Conrotatory and disrotatory processes in electrocyclic reactions (Ref 34)

Stereochemistry of electrocyclic reaction will get determined by symmetry of highest occupied molecular orbitals (HOMOs). Thermal and photochemical electrocyclic reactions always take place with opposite stereochemistry because the symmetries of the frontier orbitals (HOMO and LUMO combined) are always different. They have formulated stereochemistry rules to find out the pathway based on number of double bonds. Later they also formulated selection rules for concerted cycloaddition reactions based on symmetry of molecular orbitals [28].

In the current thesis work, the main objective was to consider a concerted reaction which obey Woodward-Hoffmann rule and study the influence of vibrational strong coupling that can possibly control the symmetry of FMOs, in turn affect the course of the reaction. For that purpose, we did literature search for liquid phase reactions happening in room temperature conditions and citronellal cyclisation reaction to isopulegol with bismuth triflate catalyst was considered as a model experiment.

2.1.2 System Under study: Cyclisation of Citronellal to Isopulegol

Monoterpenoids are a collection of naturally occurring compounds which are having isoprene units and oxygen functionality in structure. They generally find uses in food flavoring and preservation, as an ingredient in perfumes and soaps and also used in herbal and folk medicines. Citronellal is one of the most common monoterpene which

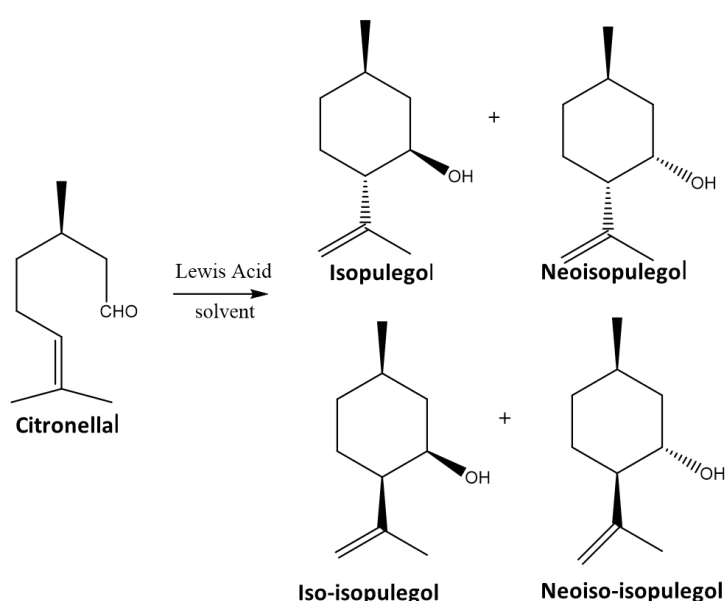


Figure 2.4 Cyclisation of Citronellal giving four diastereoisomers as products (Ref 20)

provide citronella oil its distinctive lemon scent. Citronellal ($C_{10}H_{18}O$) or 3,7-dimethyloct-6-en-1-al is usually derived from lemongrass and lemon-scented tea tree and it has strong antifungal and antiseptic traits.

Cyclization of citronellal (CNAL) to isopulegol is an intramolecular carbonyl ene reaction which has a commercial importance as it is an important step during the production of menthol, which is used to give pepper mint smell and taste to many products. This reaction is usually conducted over a Lewis acid catalyst and can lead to four diastereoisomers as products as shown in figure 2.4. They are isopulegol, iso-isopulegol, neo-isopulegol, and neoiso-isopulegol. The selectivity of this cyclization depends on different parameters which includes the Lewis acid, solvent, and reaction temperature. Some of the catalysts that have been used for this purpose include $ZnBr_2$, $Sc(OTf)_3$, $Mo(II)$ complexes silica supported heteropoly acids such as $H_3PW_{12}O_{40}$ etc.^[17]

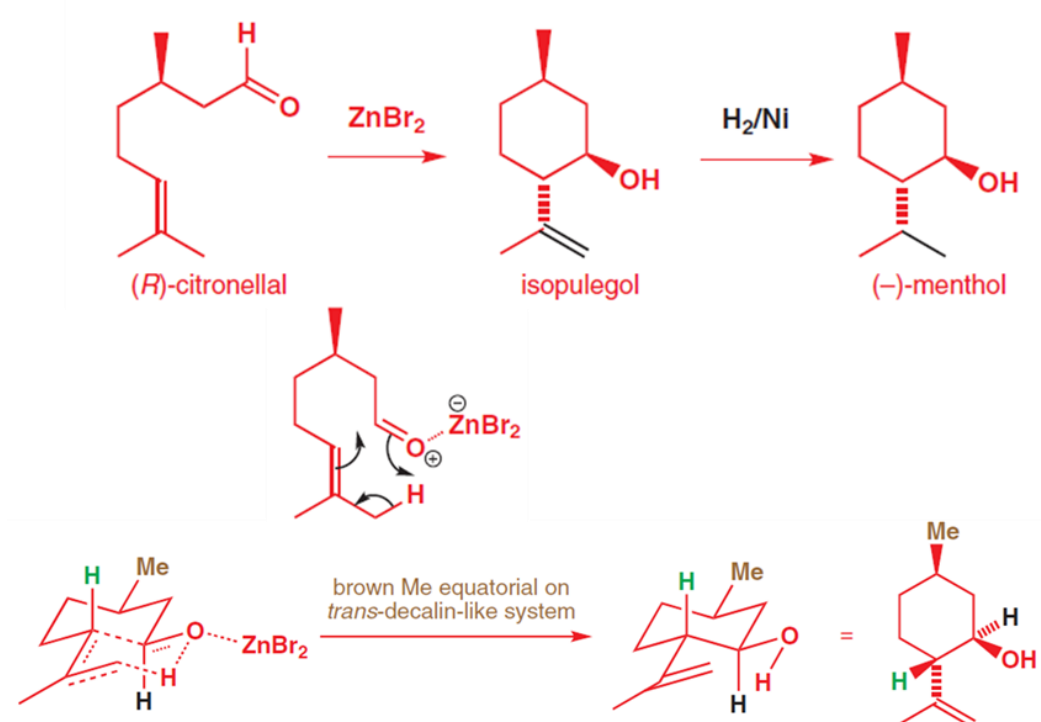


Figure 2.5 Lewis acid catalysed carbonyl ene reaction. Stereochemistry comes from an all-chair arrangement in the conformation of the transition state. The methyl group will adopt an equatorial position in this conformation, fixing the way the other bonds are formed (Ref 21)

Mechanism of cyclisation of citronellal to isopulegol catalysed with ZnBr_2 is shown in figure 2.5. It is the first step during the synthesis of menthol from citronellal. It is an example for Lewis acid catalysed intramolecular carbonyl ene reaction because in the mechanism, movement of the alkene and the closure of the ring with the formation of one new C–C bonds happens with ZnBr_2 as catalyst.

Solvent effects in Lewis acid catalysed citronellal was studied by Nicolás M. Bertero et.al. They investigated this cyclisation reaction using solvents with different polarity.^[30] They used non-polar (toluene, cyclohexane,), weakly polar (chloroform), polar protic (2-propanol, ethanol) and polar aprotic (acetonitrile) solvents. They investigated the direct solvent-CNAL interaction by FTIR for getting a better understanding of the effect of solvent-reactant interactions. Their observations are shown in Table 2.1 and they found out that effect of solvent on catalyst activity cannot be satisfactorily interpreted only in terms of solvent-CNAL interactions as determined by $\nu_{\text{C=O}}$ band shifts.

CNAL-Solvent mixture	$\nu_{\text{C=O}}$ peak of CNAL (cm^{-1})	Frequency shift $\Delta\nu_{\text{C=O}}$ (cm^{-1})
CNAL-CNAL	1725.3	-
CNAL-CHX	1731.8	6.5
CNAL-TOL	1727.3	2.0
CNAL-EtOH	1722.5	-2.8
CNAL-CLF	1722.1	-3.2
CNAL-ACN	1721.5	-3.8
CNAL-2-PrOH	1720.5	-4.8

Table 2.1 Frequency shift of the $\nu_{\text{C=O}}$ absorption band of CNAL in CNAL-solvent mixtures (Ref 30)

As said earlier different kinds of Lewis acid catalysts can be used for the cyclisation of CNAL, however many of them suffer from some drawbacks. Some of them are either very expensive and moisture sensitive, some of them are corrosive and toxic.

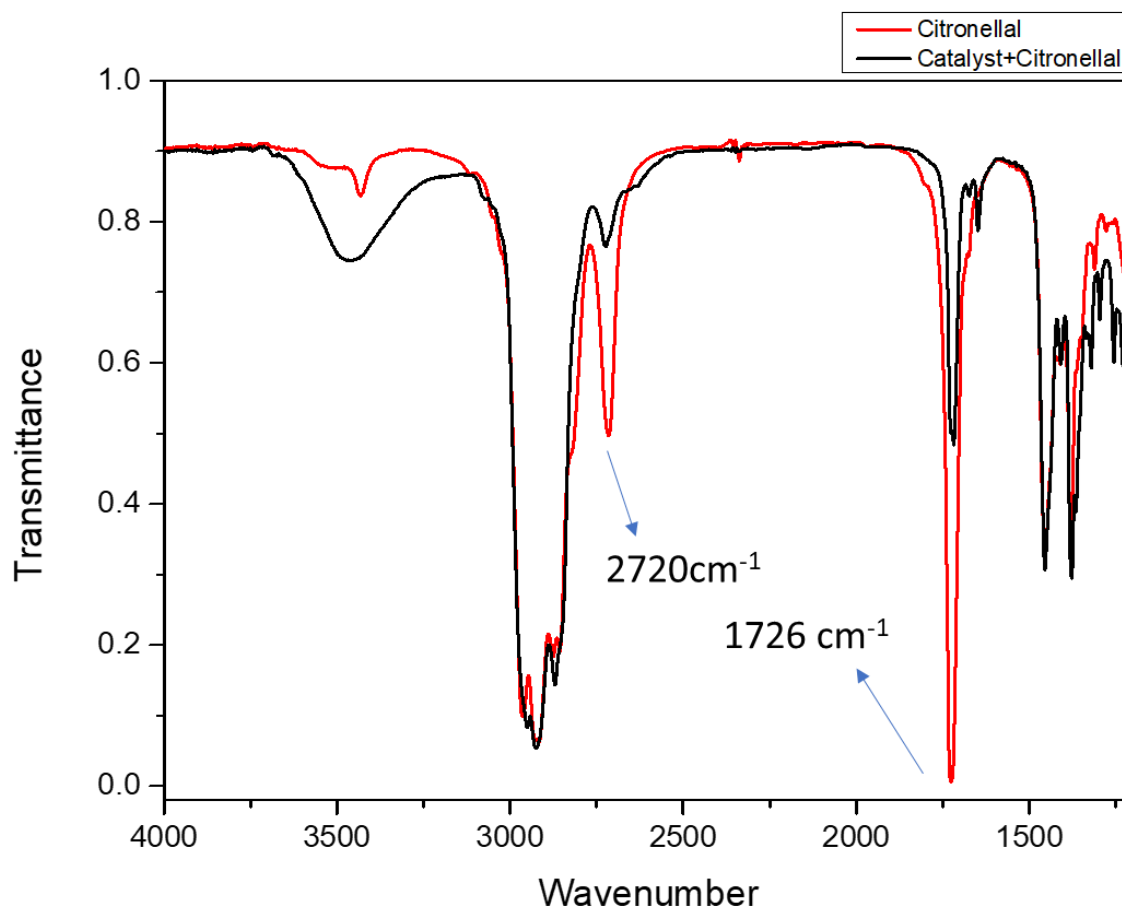


Figure 2.7 Combined FTIR spectra of Pure Citronellal and Citronellal + Catalyst (without Solvent)

2.2 Experimental Methods

Citronellal was purchased from Tokyo Chemical Industry Company. Infrared spectrum of reactant which was obtained by neat method is shown in figure 2.7. Citronellal has a carbonyl vibrational stretch at 1726 cm^{-1} and it has an ir peak of C-H of aldehyde at 2720 cm^{-1} .

For the cyclisation of citronellal to isopulegol we have used bismuth triflate ($\text{Bi}(\text{OTf})_3 \cdot x\text{H}_2\text{O}$) as catalyst and tried to use different solvents for the reaction. 50:50 (V/V) ratio of citronellal and solvent with 0.05 mol% of catalyst (with respect to the amount

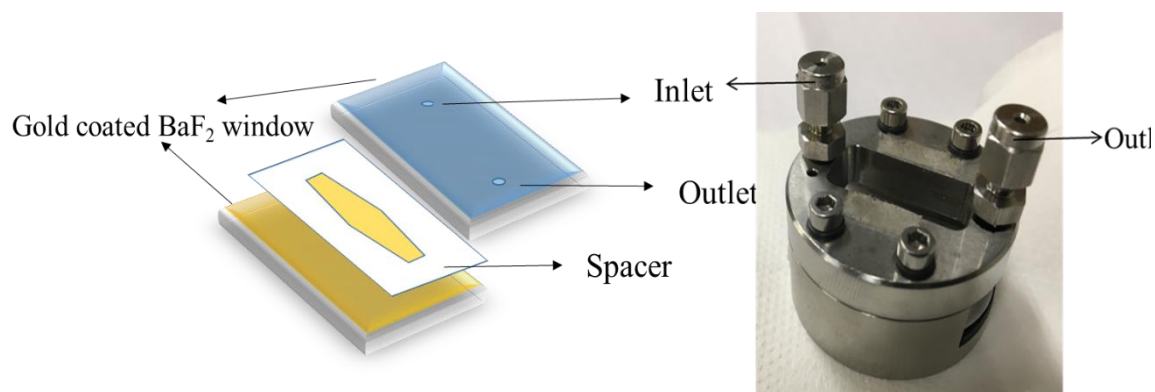


Figure 2.8 Schematic representation of a Fabry-Perot cavity and the original picture of cavity used to conduct the experiment

of citronellal) was taken for the experiment after proper optimization. Cyclohexanone was used the solvent for the reaction so that the carbonyl peak overlap around 1715 cm^{-1} .

Stock solution were prepared and $200\text{ }\mu\text{l}$ of citronellal (0.013 mmol) was added in a clean vial followed by the addition of freshly prepared catalytic solution by taking 2.13 mg ($0.007\text{ }\mu\text{mol}$, 0.05%) of bismuth triflate catalyst in $200\text{ }\mu\text{l}$ cyclohexanone. The reaction mixture was injected immediately into a flow cell microfluidic cell (non-cavity) and the reaction rates are recorded in an FTIR spectrophotometer. Microfluidic cell has two BaF_2 windows separated by $12\text{ }\mu\text{m}$ Mylar spacer.

Cavity experiments were conducted in a Fabry-Perot cavity, which was made from gold coated BaF_2 windows (10 nm gold sputtered on top of BaF_2 windows) separated by $12\text{ }\mu\text{m}$ Mylar spacer and followed the similar procedure as said earlier.

2.3 Results and Discussions

Experiment was conducted in non-cavity and cavity conditions and it was observed using a high resolution FTIR spectrometer at room temperature.

2.3.1 Kinetics under Non-cavity conditions

Reaction was observed by plotting the change in IR spectra with respect to time. During the course of reaction gradual decreasing of transmittance with time was observed in the 2720 cm^{-1} peak which corresponds to C-H of aldehyde of the citronellal. Non-cavity experiments were conducted at least two times and first order kinetic rate was calculated from the bleaching curve by exponential decay fit method or by initial rate method. Tentative kinetic graphs are shown in figure 2.9.

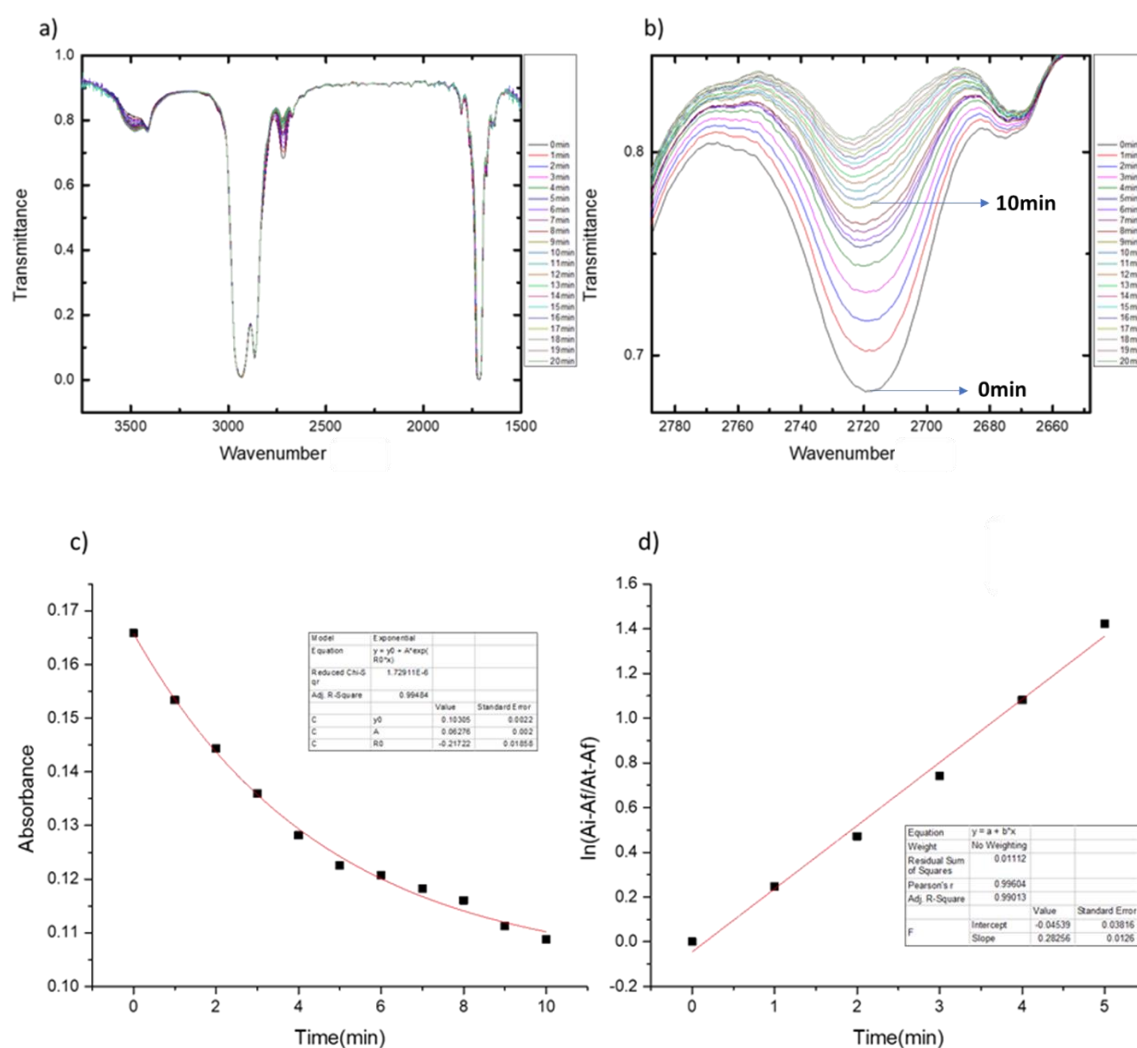


Figure 2.9 a) Combined FTIR data with time b) Zoomed spectra of peak at 2720 cm^{-1} c) and d) first order kinetics plot to find out the reaction rate with 0.05% of catalyst

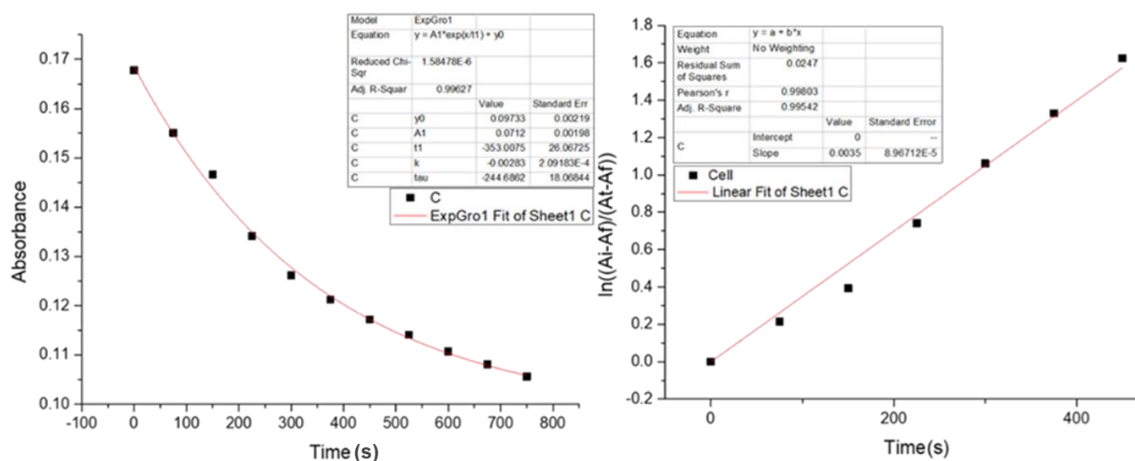


Figure 2.10 First order kinetics plots to find out the reaction rate with 0.02% of catalyst

From transmittance, absorbance values were calculated using the equation

$$A = -\log(T)$$

The reaction in non-cavity condition with different concentrations of catalyst was done and the average reaction rate obtained for 0.05% and 0.02% of the catalyst was $4.73 \times 10^{-3} \text{ s}^{-1}$ and $3.5 \times 10^{-3} \text{ s}^{-1}$, respectively. The above mentioned reaction rate was calculated using initial rate method or linear regression method by observing the change in absorbance value in the peak at 2720 cm^{-1} . The C=O peak in citronellal at 1726 cm^{-1} should also be changing with time but there is an overlap of carbonyl peak in the solvent (cyclohexanone at 1715 cm^{-1}) and the reacting species will not permit us to follow the C=O functional group disappearance.

2.3.2 Kinetics under Cavity Conditions

We found the average rate of reaction in a microfluidic cell in non-cavity conditions for the cyclisation of citronellal was roughly $3\text{-}4 \times 10^{-3} \text{ s}^{-1}$ depending on the catalyst loading. Later, we tried to do the same in the cavity to find out the effect of vibrational strong coupling with this reaction. Here, we tried to couple the carbonyl band of citronellal at 1726 cm^{-1} to one of the cavity modes and follow the kinetic rates. F-P cavity was tuned to obtain the ON resonance condition and kept it undisturbed for 15 minutes

initially and the coupling conditions are calculated before injection of the reaction mixture. The cavity mode position can be calculated from an empty cavity structure by back calculation if the effective refractive index of the medium is known. Free spectral range (FSR) of a cavity can be obtained using the following equation:

$$\text{FSR} = \frac{10^4}{2nL}$$

Where n is the refractive index of the injecting medium and L is the thickness of spacer used (here; 12 μm). Refractive index values of Citronellal, Cyclohexanone and isopulegol are 1.447, 1.447 and 1.471 respectively.

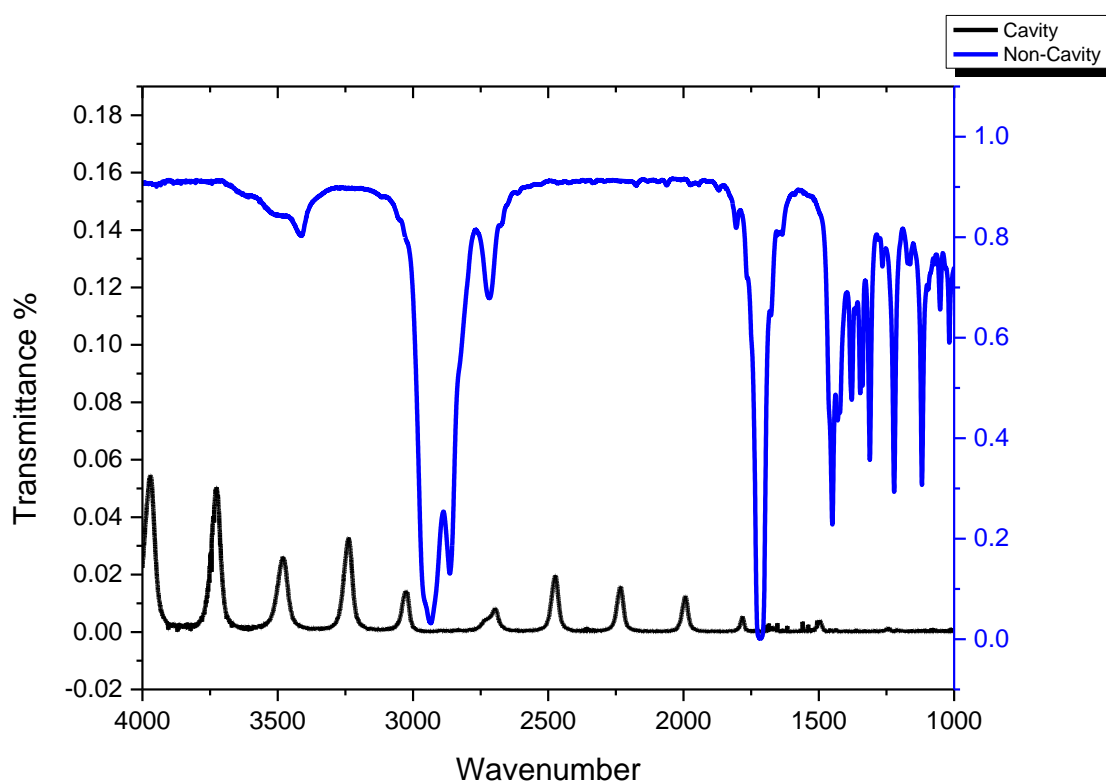


Figure 2.11 Combined spectra of cavity and non-cavity data at zero minute

VSC was achieved by coupling the C=O band to 7th mode of cavity. Here, C-H of the aldehyde during the course of the reaction cannot be decomposed as the cavity modes kill the information about the temporal changes in the band positions. We used temporal shift in the FSR values to extract the data from the strong coupling kinetic experiments. FSR of the cavity mode changes if the effective RI varies and we incorporated the variation and plotted the change in FSR value versus time to obtain the first-order reaction rate.

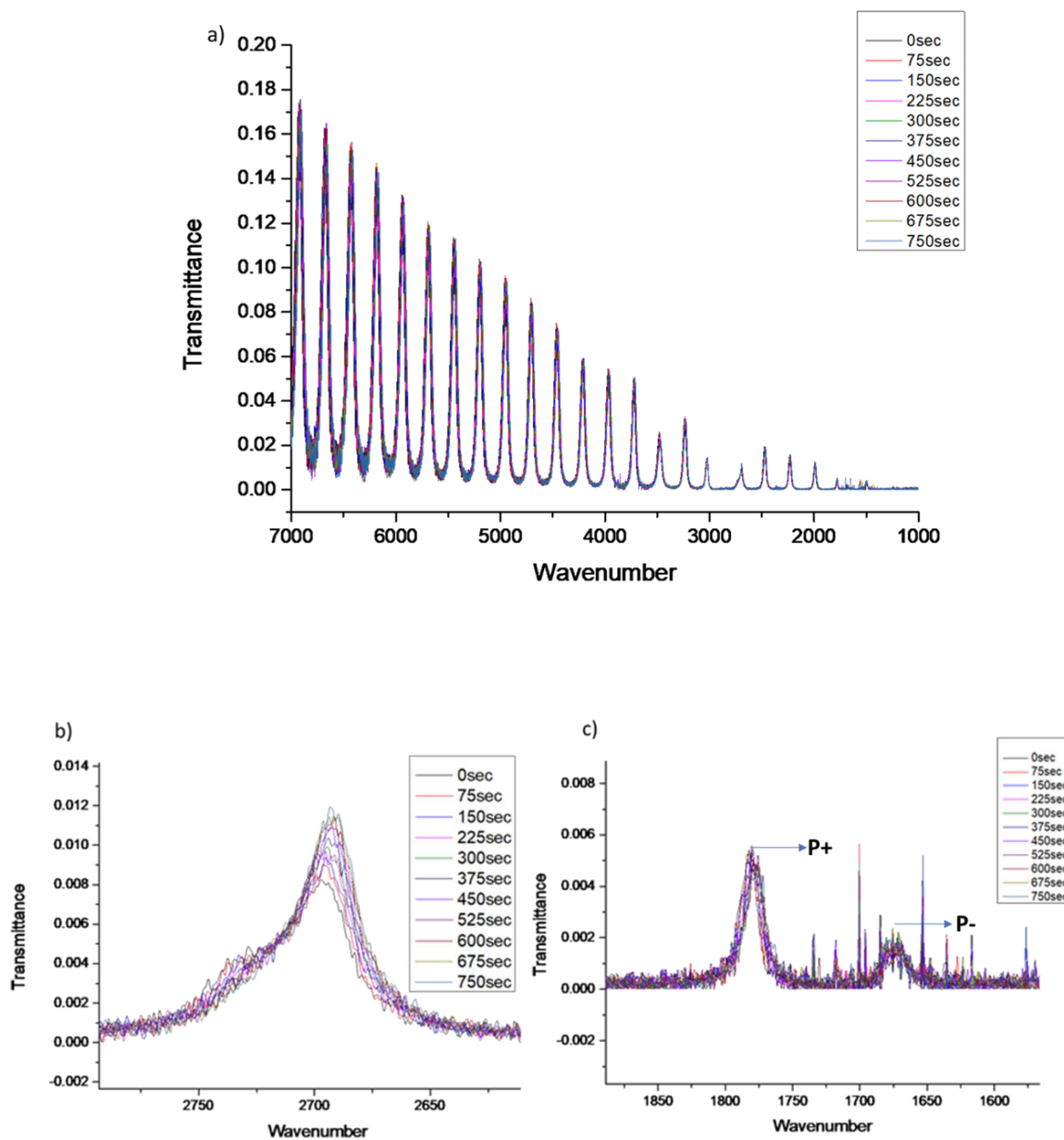


Figure 2.12 a) Cavity data of 0.02% catalyst + cyclohexanone + citronellal reaction observed for 750 seconds b) Zoomed region around 2720cm⁻¹ c) Strong coupled region for the carbonyl band of citronellal in cyclohexanone.

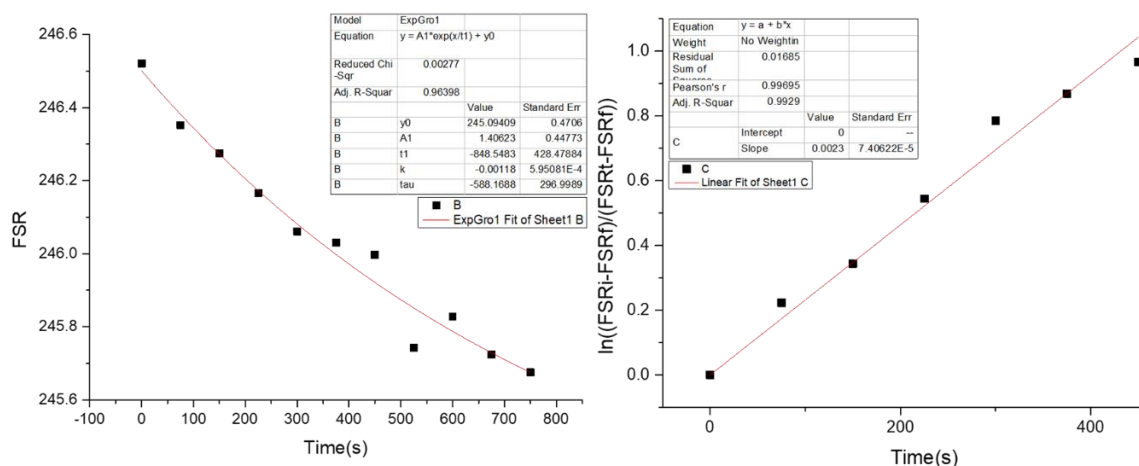


Figure 2.13 Reaction rate calculation using FSR shift method for ON resonance cavity.

We found the reaction rate follow first-order kinetic and hence tried to fit in an exponential curve and also using linear regression method. The rate obtained from linear regression method was $2.3 \times 10^{-3} \text{ s}^{-1}$ with R^2 fitting value of 99% as shown in figure 2.13. FSR fit method gives a decrease in the rate of the reaction under strong coupling citronellal C=O band to the cavity field. FSR method gives a change of 1.5 times retardation in the rate using linear regression method

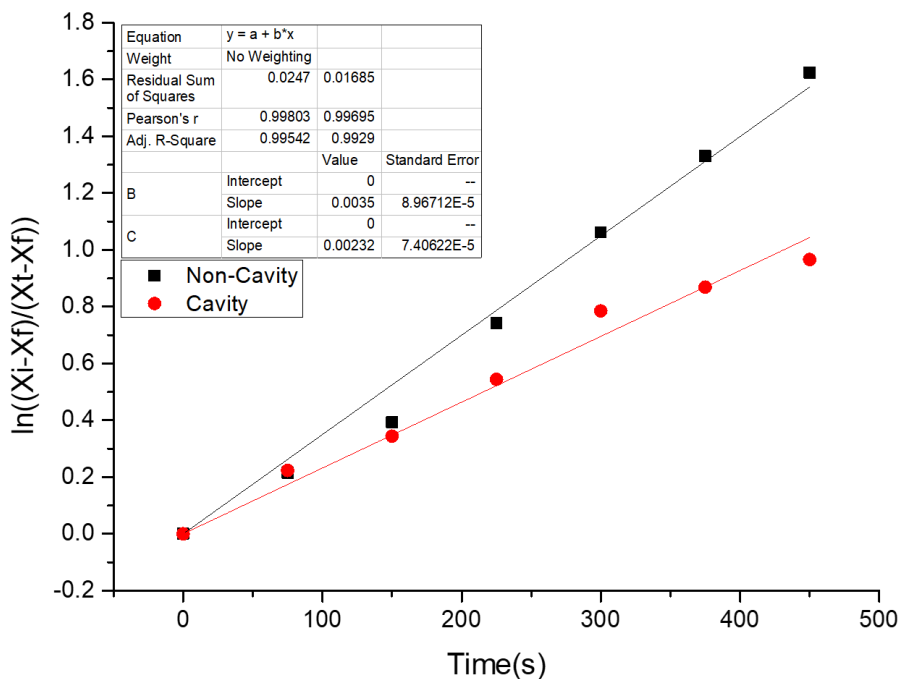


Figure 2.14 Combined first order initial rate calculation plots of cell and cavity data

2.4 Conclusions

In the current thesis, we tried to conduct the cyclisation of Citronellal to Isopulegol using bismuth triflate as catalyst and cyclohexanone as solvent in cavity and non-cavity conditions. It was observed that the reaction is following a first-order kinetics. We have calculated the rate of reaction in non-cavity and cavity condition using different methods. We used 0.02% of catalyst with respect to citronellal and equal volume of solvent. The reaction rate obtained in non-cavity condition was $3.5 \times 10^{-3} \text{ s}^{-1}$ and from the cavity by using the temporal shifts in FSR values the rate obtained was $2.3 \times 10^{-3} \text{ s}^{-1}$. Therefore, we can conclude that a slowing down of reaction was observed inside the cavity conditions by approximately more than 1.5 times than in non-cavity conditions.

Future aspects of the research include conducting the same with other solvents and with various concentrations to observe the effect of vibrational strong coupling and its influence on controlling the reaction due to co-operative effects. Temperature dependent studies are also required to understand the free energy changes associated with a concerted reaction under VSC. Efforts are under way to find out model systems that exactly follow Woodward-Hoffmann symmetry rules and to see how it will affect the symmetry of frontier molecular orbitals.

Bibliography

- [1] S. Haroche, “A short history of Cavity Quantum Electrodynamics,” in Conference on Coherence and Quantum Optics, *Optical Society of America*, (2007)
- [2] T. Hümmer, F. J. García-Vidal, L. Martín-Moreno, and D. Zueco, “Weak and strong coupling regimes in plasmonic QED” *Phys. Rev. B* *87*, 115419 (2013)
- [3] A. Einstein, “The Quantum Theory of Radiation” *Physikalische Zeitschrift* *18*, 121(1917)
- [4] M. G. Raizen, R. J. Thompson, R.J. Brecha, H. J. Kimble, and H.J. Carmichael “Normal-mode splitting and linewidth averaging for two-state atoms in an optical cavity” *Phys. Rev. Lett.* *63*, 240 (1989)
- [5] C. Weisbuch,, M. Nishioka, A. Ishikawa, and Y. Arakawa “Observation of the Coupled Exciton-Photon Mode Splitting in a Semiconductor Quantum Microcavity” *PhysRevLett.**69.3314* (1992)
- [6] D. S. Dovzhenko, a S. V. Ryabchuk, a Yu. P. Rakovich a,b,c and I. R. Nabiev , “Light–matter interaction in the strong coupling regime: configurations, conditions, and applications” *Nanoscale*, *10*, 3589 (2018)
- [7] Bitarafan, M.H.; DeCorby, R.G. “On-Chip High-Finesse Fabry-Perot Microcavities for Optical Sensing and Quantum Information.” *Sensors*, *17*, 1748.(2017)
- [8] E.T. Jaynes ; F.W. Cummings “Comparison of Quantum and Semiclassical Radiation Theories with Application to the Beam Maser” *Proceedings of the IEEE*, vol. 51, no. 1, pp. 89-109(1963)
- [9] Yakovlev, V. A.; Nazin, V. G.; Zhizhin, G. N. “The surface polariton splitting due to thin surface film LO vibrations” *Optics Communications.**15*, 293-295(1975)
- [10] Y. Kaluzny, P. Goy, M. Gross, J.M. Raimond, and S. Haroche, “Observation of Self-Induced Rabi Oscillations in Two-Level Atoms Excited Inside a Resonant Cavity: The Ringing Regime of Superradiance” *PhysRevLett.**51.1175* (1983)
- [11] Hutchison, J.A. et al. “Tuning the work-function via strong coupling” *Adv.Mater.**25*, 2481-2485(2013)

- [12] Thomas W. Ebbesen, “Hybrid Light–Matter States in a Molecular and Material Science Perspective” *Acc Chem Res.*49(11):2403-2412.(2016)
- [13] M. Hertzog, Mao Wang, J Mony and K Borjesson, “Strong light–matter interactions: a new direction within chemistry” *Chem. Soc. Rev.*,48, 937-961(2019)
- [14] J Lather, P Bhatt, A Thomas, T W. Ebbesen, J George, “Cavity Catalysis by Cooperative Vibrational Strong Coupling of Reactant and Solvent Molecules” *Angew.Chem. Int.Ed.* 58,10635 –10638(2019)
- [15] A.Thomas, J.George, M.Dryzhakov,S.J.Varma, J.Moran, T. Chervy, X. Zhong, E.Devaux, C.Genet, J.A.Hutchison and T.W.Ebbesen “Ground state chemistry under vibrational strong coupling: dependence of thermodynamic parameters on the Rabi splitting energy” *Angew.Chem.Int. Ed.*55,11462 –11466(2016)
- [16] J. George, A. Shalabney, J. Hutchison, C Genet and T W. Ebbesen, “Liquid-Phase Vibrational Strong Coupling” *J. Phys. Chem. Lett.* 2015, 6, 6, 1027-1031(2015)
- [17] R.S. Mohan, E.D Anderson, J.J Ernat, M.P Nguyen and A.C Palma “Environment Friendly Organic Synthesis Using Bismuth Compounds. An Efficient Method for Carbonyl-ene Reactions Catalyzed by Bismuth Triflate” *Tetrahedron Letters* 46 7747–7750 (2005)
- [18] Hutchison JA, Schwartz T, Genet C, Devaux E, Ebbesen TW. “Modifying chemical landscapes by coupling to vacuum fields”. *Angew Chem Int Ed* 2012;51:1592–1596 (2012)
- [19] Serge Haroche and Daniel Kleppner, “Cavity Quantum Electrodynamics” *Phys. Today* 42(1), 24 (1989)
- [20] C.K.Z. Andrade, O.E.Vercillo, J.P. Rodrigues and D.P. Silveira “Intramolecular ene reactions catalyzed by NbCl₅, TaCl₅ and InCl₃” *J. Braz. Chem. Soc.*vol.15 no.6(2004)
- [21] J. Clayden, N.Greeves, S.G Warren – “Organic chemistry”, Chapter 34 *Oxford University Press*(2012)
- [22] K.Fukui, T.Yonezawa, and H. Shingu , “A Molecular Orbital Theory of Reactivity in Aromatic Hydrocarbons” *J. Chem. Phys.* 20, 722 (1952)

- [23] E. M. Purcell, H. C. Torrey, and R. V. Pound “Resonance Absorption by Nuclear Magnetic Moments in a Solid” *Phys. Rev.* 69, 37(1945)
- [24] T. Hummer, F. J. Garcia-Vidal, L. Martin-Moreno, and D. Zucco, “Weak and strong coupling regimes in plasmonic QED” *Phys. Rev.* 87, 115419 (2013)
- [25] T Schwartz, J A. Hutchison, C Genet, S Haacke, and Thomas W. Ebbesen “Polariton Dynamics under Strong Light–Molecule Coupling” *ChemPhysChem* 14, 125 – 131(2013)
- [26] A. Tsargorodska, M.L. Cartron, C. Vasilev, G. Kodali, O.A. Mass, J.J. Baumberg, P.L. Dutton, C.N. Hunter, P. Torma and G. J. Leggett “Strong Coupling of Localized Surface Plasmons to Excitons in Light-Harvesting Complexes” *Nano Lett.*, 16, 6850–6856(2016)
- [27] D. Meschede and H. Walther “One-Atom Maser” *PhysRevLett.* 54.551 (1985)
- [28] R. B. Woodward and R. Hoffmann, “Selection Rules for Concerted Cycloaddition Reactions” *J. Am. Chem. Soc.*, 87, 2046-2048(1965)
- [29] R. B. Woodward and R. Hoffmann, “Stereochemistry of Electrocyclic Reactions” *J. Am. Chem. Soc.*, 87, 395 (1965)
- [30] N M. Bertero, I, A F. Trasarti, M C. Acevedo, A J Marchi, and C R Apesteguía, “Solvent effects in solid acid-catalyzed reactions: The case of the liquid-phase isomerization/cyclization of citronellal over SiO₂-Al₂O₃” *Molecular Catalysis* (2018)
- [31] B L. Jensen, A Malkawi, and V McGowan, “Cyclization of the Monoterpene Citronellal to Isopulegol: W A Biomimetic Natural Product Synthesis” *J. Chem. Educ.* 77, 11, 1474 (2000)
- [32] P Kocovsky, G Ahmed, J Srogl, A V. Malkov, and J Steele “New Lewis-Acidic Molybdenum(II) and Tungsten(II) Catalysts for Intramolecular Carbonyl Ene and Prins Reactions. Reversal of the Stereoselectivity of Cyclization of Citronellal” *J. Org. Chem.* 64, 2765-2775(1999)
- [33] E. M. Purcell, H. C. Torrey, and R. V. Pound “Resonance Absorption by Nuclear Magnetic Moments in a Solid” *Phys. Rev.* 69, 37 (1946)
- [34] J E. McMurry “Organic Chemistry with Biological Applications” Chapter 26 (2015)