

## **Chem-02843 COURSE Material Bundle**

### **Organic Special (BS-VIII)**

#### **Contents**

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# *The Islamia University Bahawalpur*

## **Department of Chemistry**

BS (VIII Semester) CHEM-02843  
Credit Hours: 04

Organic Spectroscopy

Instructor:	Prof. Dr. Shazia Anjum	Class Room:	Office
Class Day:	Monday-Thursday	Class Timing:	4.00-5:00 pm

### **Course Objectives:**

Students will acquire an adequate knowledge about fundamental and instrumental aspects of different spectroscopic techniques and will be able to perform structural elucidation of organic compounds using spectral data.

### **Course Contents:**

#### **UV-Visible:**

Basic concepts, electronic transitions, Lambert-Beer's law, factors influencing the lambda max ( $\lambda_{\text{max}}$ ) values, Woodward rules for calculation of wavelength values.

#### **IR spectroscopy:**

Basic concepts, absorption mechanisms, functional group determination and factors affecting the absorption frequencies.

#### **$^1\text{H}$ -NMR and $^{13}\text{C}$ -NMR:**

Chemical shift, factors affecting chemical shift, spin relaxation, spin-spin coupling, coupling constants, nuclear overhauser effect, 2-D NMR, COSY and HETCOR.

#### **Mass Spectrometry:**

Basic concepts; mass spectrometers, ionization techniques, different fragmentation patterns and structure elucidation, combined usage of IR, UV, NMR and Mass spectrometric data for structure elucidation of organic compounds having medium complexity.

Week 1	UV-Visible: Basic concepts, electronic transitions, Lambert-Beer's law, factor influencing lambda max values
Week 2	Woodward rules for calculation of wavelength values
Week 3	Infra red spectroscopy: Basic Concept, absorption mechanism
Week 4	Functional group determination and factors affecting the absorption frequencies
Week 5	Mass spectrometry: Basic concepts, mass spectrometers, ionization techniques
Week 6	Different mass fragmentation patterns and structure elucidation
Week 7	Different mass fragmentation patterns and structure elucidation
Week 8	Review
Week 9	<b>Mid Term Examination</b>

Week 10	<sup>1</sup> HNMR:Basic Concepts
Week 11	Chemical shift, factors affecting chemical shift, spin relaxation, spin-spin coupling
Week 12	<sup>13</sup> CNMR:Basic Concepts
Week 13	Nuclear overhauser effect, 2-D NMR, COSY and HETCOR
Week 14	Combined usage of IR, UV, NMR and Mass spectrometric data for structure elucidation of organic compounds having medium complexity.
Week 15	Combined usage of IR, UV, NMR and Mass spectrometric data for structure elucidation of organic compounds having medium complexity.
Week 16	Combined usage of IR, UV, NMR and Mass spectrometric data for structure elucidation of organic compounds having medium complexity.
Week 17	Review
Week 18	<b><i>Final Term Examination</i></b>

### APPOINTMENT WITH THE INSTRUTORS

Prof. Dr. Shazia Anjum will be available in her office Monday to Friday during office hours.

### Recommended Books:

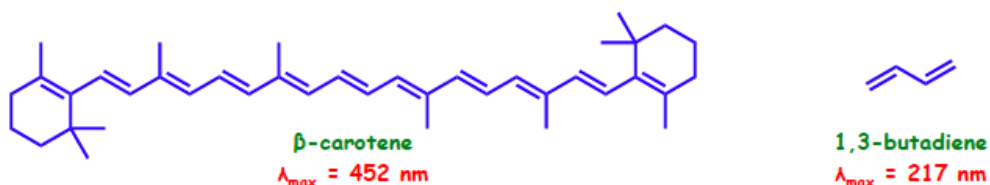
1. William Kemp, *Organic Spectroscopy*, 3<sup>rd</sup> ed., Macmillan Press Ltd. Hong Kong (1991).
2. Kalsi, P. S., *Spectroscopy of Organic Compounds*, 6<sup>th</sup> ed., New Age International, New Delhi, India, (2007).
3. Yadav, L. D. S., *Organic Spectroscopy*, Springer, UK, (2005).
4. Robert M. Silverstein, Francis X. Webster, David J. Kiemle, *Spectrometric Identification of Organic Compound*, 7<sup>th</sup> ed., John-Wiley & Sons, Inc., (2005).
5. Hollas, J. M., *Modern Spectroscopy*, 4<sup>th</sup> ed., John-Wiley & Sons, Inc., (2004).
6. Donald L. Pavia, Gary M. Lampman, George S. Kriz, *Introduction to Spectroscopy*, 3<sup>rd</sup> ed., Thomson Learning, Austraila, (2001).
7. Williams, D. H. and Flemming, I., *Spectroscopic Methods in Organic Chemistry*, 6<sup>th</sup> ed., McGraw-Hill Higher Education, (2008).

## **Lecture Notes**

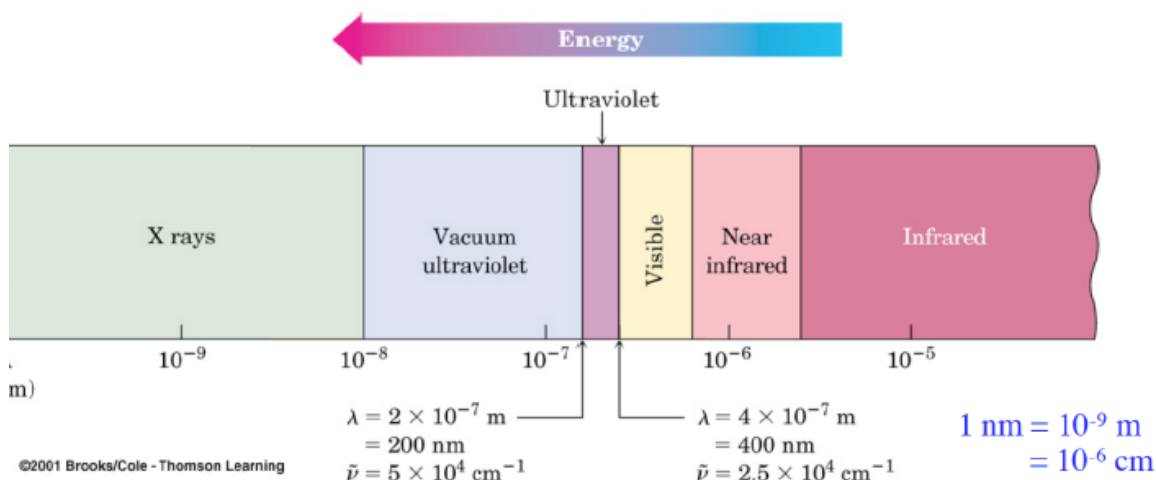


UV-Visible: Basic concepts, electronic transitions, Lambert-Beer's law,  
factor influencing lambda max values

- UV light can be absorbed by molecules to excite higher energy (most loosely bound) electrons from lower energy states to higher states.
- Such transitions can be studied extensively to understand the binding energy of the corresponding electrons undergoing transition.
- Since  $\pi$ -electrons are most loosely bound in an organic molecule, UV spectroscopy yields a lot of information about the degree of unsaturation in a molecule.
- When the wavelength of the transition exceeds the UV range, based on the same principle, even the colours of molecules can be explained on the basis of absorption of visible light.

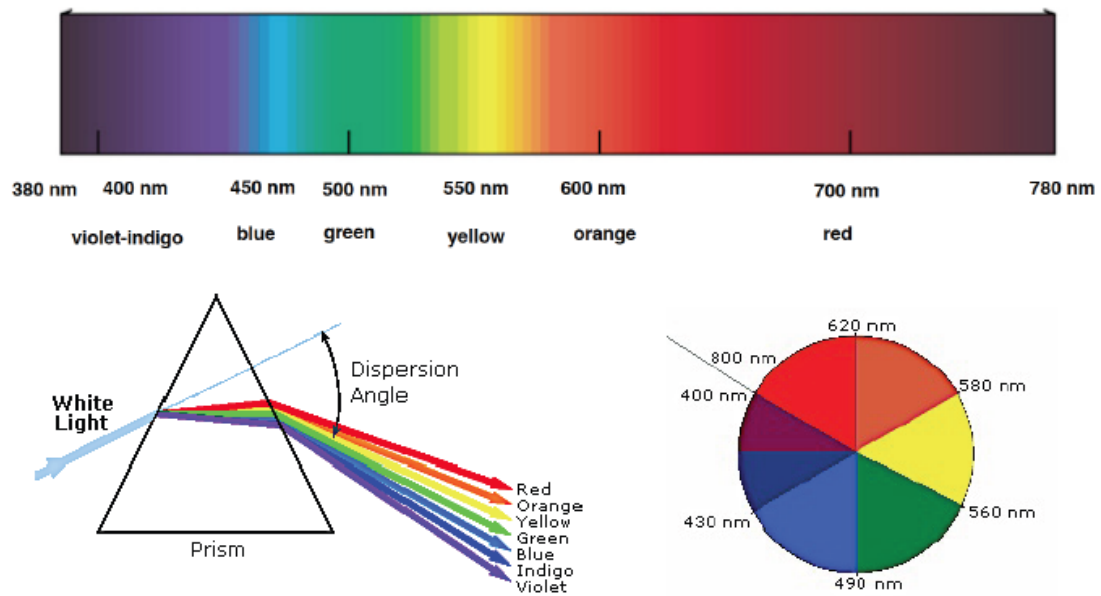


*Electromagnetic Spectrum*



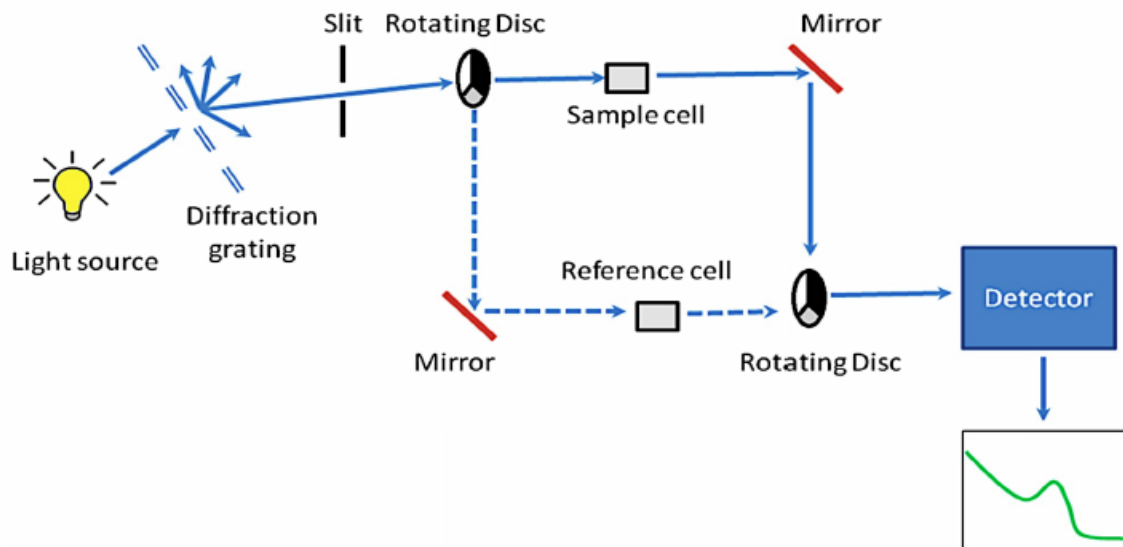
Energy is proportional to frequency  
Frequency is inversely proportional wavelength

## *The Visible spectrum*



## *Instrumentation*

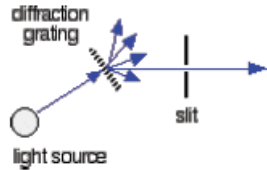
### Double Beam UV Spectrometer:



## Light Source:

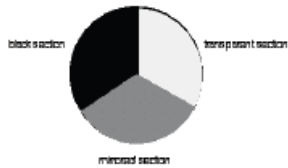
- Combined sources used to cover a range of 200–800 nm
- Deuterium lamp for UV range
- Tungsten/halogen for visible range

## Diffraction Grating & The Slit:



- Diffraction grating splits lights to its component colors like a prism
- Slit allows to pass only a narrow range of wavelengths to the rotating disk

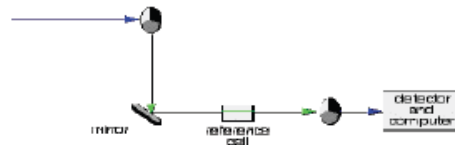
## Rotating Disks:



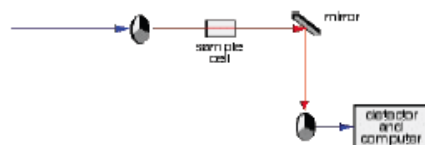
- Rotating disks are made of different number of segments

## Rotating Disks:

- If light hits the mirrored section, it bounces back to a mirror. The reflected light meets the transparent section of the second disk and passes through it to the detector.



- If light hits the transparent section, it will pass through and be bounced by a mirror onto a second rotating disk. Light meets the mirrored section of the second disk and bounces onto the detector.



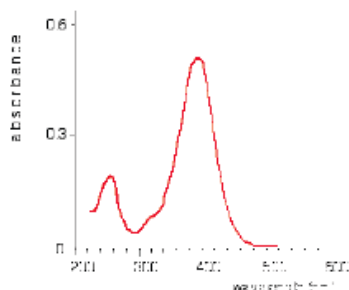
## Sample & Reference Cells:



- Small rectangular glass/quartz containers.
- Designed in such a manner that light has to travel 1 cm through the contents.

## Detector & Computer:

- Detector converts light to current. The greater is the intensity of light, the higher is the current.
- An absorbance (A) could be written as-



$$A = \log_{10} \frac{I_0}{I}$$

Intensity of light passing through reference cell =  $I_0$

Intensity of light passing through sample =  $I$

## Principle of UV spectroscopy

UV spectroscopy obeys the Beer-Lambert law, which states that: *when a beam of monochromatic light is passed through a solution of an absorbing substance, the rate of decrease of intensity of radiation with thickness of the absorbing solution is proportional to the incident radiation as well as the concentration of the solution.* The expression of Beer-Lambert law is:-

$$A = \log (I_0/I) = Ecl$$

Where, A = absorbance

$I_0$  = intensity of light incident upon sample cell

I = intensity of light leaving sample cell

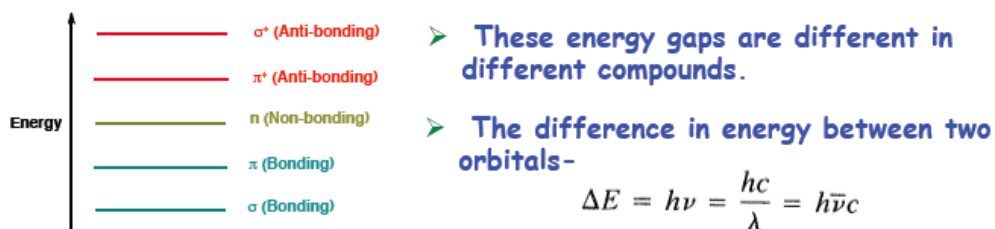
C = molar concentration of solute

L = length of sample cell (cm.)

E = molar absorptivity

From the Beer-Lambert law it is clear that greater the number of molecules capable of absorbing light of a given wavelength, the greater the extent of light absorption. This is the basic principle of UV spectroscopy.

## Relative Energies of Various Orbitals:

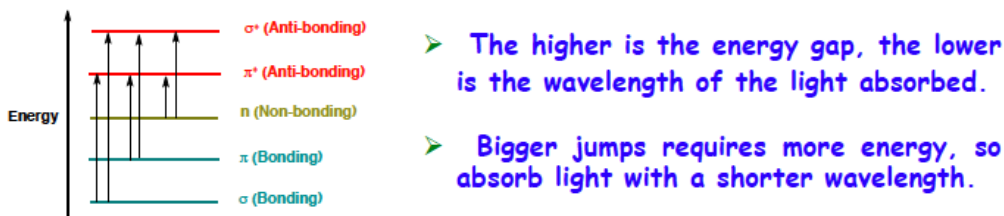


- When light passes through a compound, some of its energy promotes an electron from one of the bonding or non-bonding orbitals to one of the anti-bonding orbitals.
- The frequency (or wavelength) of absorption depends on the energy gaps between those two energy levels.

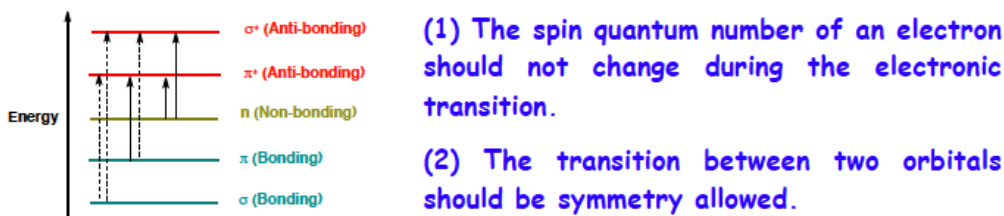
$$\Delta E = h\nu = \frac{hc}{\lambda}$$

speed of light:  $c = \lambda \nu$  frequency (Circles to  $\nu$ ,  $\mu$ )

## Electronic Transitions



- Not all electronic transitions are allowed. Certain restrictions should be considered for electronic transitions, called "selection rules"



- Any transition that violates these rules are called "forbidden transition". Most common "forbidden transition" is  $n \rightarrow \pi^*$ .

### Important Electronic Transitions:

- From  $\pi$  (bonding) orbital to  $\pi^*$  (anti-bonding) orbital ( $\pi \rightarrow \pi^*$ ).
- From  $n$  (non-bonding) orbital to  $\pi^*$  (anti-bonding) orbital ( $n \rightarrow \pi^*$ ).
- From  $n$  (non-bonding) orbital to  $\sigma^*$  (anti-bonding) orbital ( $n \rightarrow \sigma^*$ ).
- In Alkanes:
  - $\sigma \rightarrow \sigma^*$  or  $n \rightarrow \sigma^*$
  - Usually weak absorptions

#### Absorption Characteristics of $n \rightarrow \pi^*$

Compound	$\lambda_{\max}$	$\epsilon_{\max}$	Solvent
Methanol	177	200	Hexane
1-Hexanethiol	224 (s)	126	Cyclohexane
Trimethylamine	199	3950	Hexane
N-methylpiperidine	213	1600	Ether
Diethyl ether	188	1995	Gas phase
Methyl chloride	173	200	Hexane
Methyl iodide	259	400	Hexane

#### ➤ In Alkenes:

In unconjugated alkenes  $\pi \rightarrow \pi^*$  transition takes place around 170-190 nm.

#### Absorption Data for Conjugated Alkenes ( $\pi \rightarrow \pi^*$ )

Compound	$\lambda_{\max}$	$\epsilon_{\max}$	Solvent
1,3-Butadiene	217	21,000	Hexane
2,3-Dimethyl-1,3-butadiene	226	21,400	Cyclohexane
1,3,5-Hexatriene	253	50,000	Isooctane
	263	52,000	
	274	50,000	
1,3-Cyclohexadiene	256	8,000	Hexane
1,3-Cyclopentadiene	239	3,400	Hexane

- In Carbonyls:  $\pi \rightarrow \pi^*$  around 190 nm ( $\epsilon = 900$ ) &  $n \rightarrow \pi^*$  around 280 nm ( $\epsilon = 15$ ).

Since  $n \rightarrow \pi^*$  transition is a symmetry forbidden transition, intensity of this transition is much lower than other allowed transitions.

Chromophore		Example	Excitation	$\lambda_{\max}$	$\epsilon_{\max}$	Solvent
$C=C$		Ethene	$\pi \rightarrow \pi^*$	165 nm	15,000	hexane
$C\equiv C$		1-Hexyne	$\pi \rightarrow \pi^*$	173 nm	10,000	hexane
$C=O$		Ethanal	$n \rightarrow \pi^*$ $\pi \rightarrow \pi^*$	290 nm 180 nm	15 10,000	hexane hexane
$N=O$		Nitromethane	$n \rightarrow \pi^*$ $\pi \rightarrow \pi^*$	275 nm 200 nm	17 5,000	ethanol ethanol
$C-X$	$X=Br$	Methyl bromide	$n \rightarrow \sigma^*$	205 nm	200	hexane
	$X=I$	Methyl Iodide	$n \rightarrow \sigma^*$	255 nm	360	hexane

➤ **Chromophore:**

A covalently unsaturated group responsible for electronic absorption (e.g.,  $C=C$ ,  $C=O$ , esters, amides,  $-NO_2$  etc.).

➤ **Auxochrome:**

A saturated group with non-bonded electrons which, when attached to a chromophore, alters both the wavelength and the intensity of the absorption (e.g.,  $-OH$ ,  $-NH_2$ ,  $-NR_2$ ,  $-SH$  etc.)

➤ **Bathochromic Shift:**

The shift of absorption to a longer wavelength (also known as "red shift").

➤ **Hypsochromic Shift:**

The shift of absorption to a shorter wavelength (also known as "blue shift").

➤ **Hyperchromic Effect:** An increase in absorption intensity.

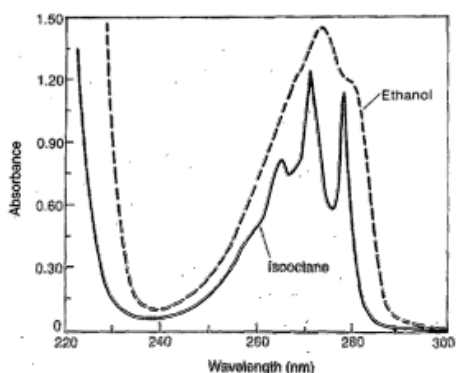
➤ **Hypochromic Effect:** A decrease in absorption intensity.

## Solvents & Solution

➤ Solvents should not absorb UV-radiation within same range as the substance.

Acetonitrile	190 nm	<i>n</i> -Hexane	201 nm
Chloroform	240 nm	Methanol	205 nm
Cyclohexane	195 nm	Isooctane	195 nm
1,4-Dioxane	215 nm	Water	190 nm
95% Ethanol	205 nm	Trimethyl phosphate	210 nm

➤ A strong absorbing solvent allows very little amount of light to pass through the sample.



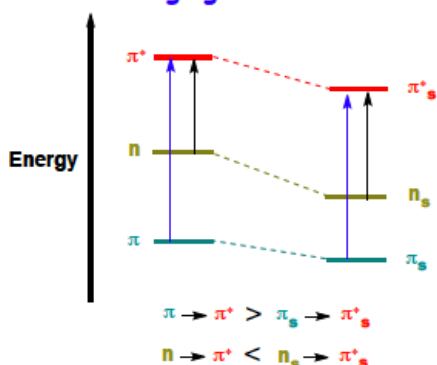
➤ Non-polar solvents do not form H-bond with solute, so "fine structure" is often observed.

➤ Polar solvents form solute-solvent complexes through H-bonding, hence, "fine structure" may disappear.

## Solvent Effects:

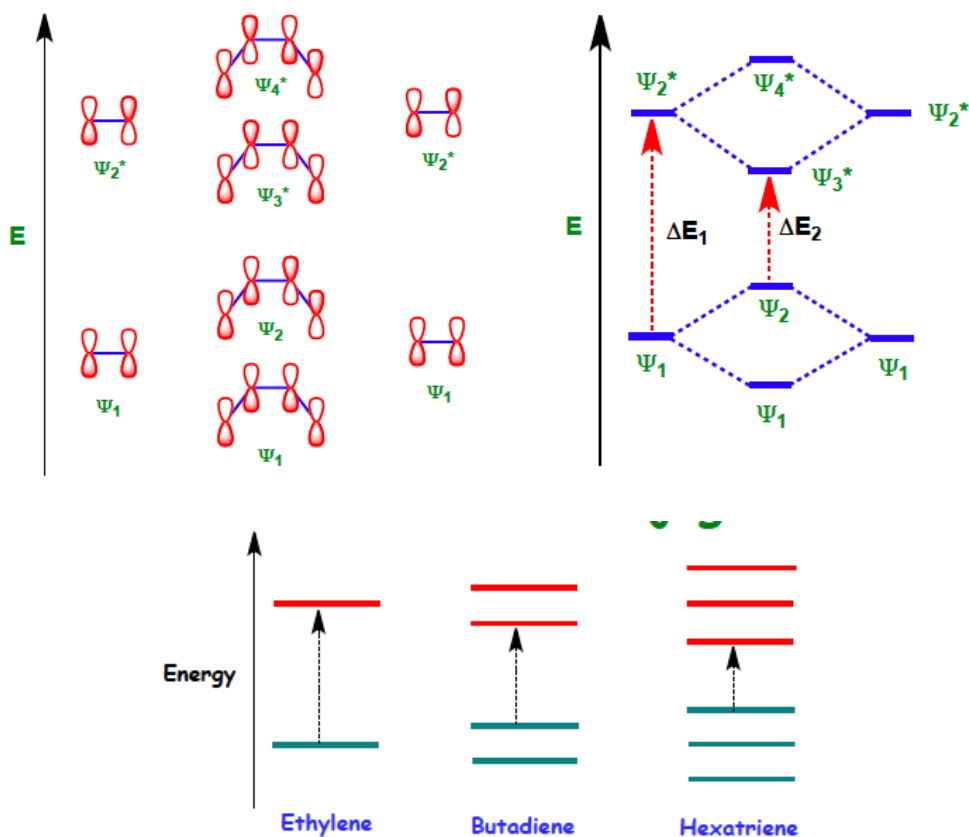
The position and intensity of an absorption band may shift if the spectrum was recorded in different solvents.

- Conjugated dienes and aromatic hydrocarbons experience very less "solvent effect".
- $\alpha,\beta$ -Unsaturated carbonyls show two different shifts in bands for changing solvents from non-polar to a polar protic one.



- $\pi \rightarrow \pi^*$  band moves to longer wavelength,  $n \rightarrow \pi^*$  band moves to shorter wavelength.
- $\pi^*$  orbitals get stabilized (due to more polarity) by solvation than  $\pi$  orbitals.  $n$  orbitals get stabilized mainly by H-bonding.

## Effect of Conjugation





## Molecule

$\lambda_{\max}$  (nm)

Ethylene

165

1,3-butadiene

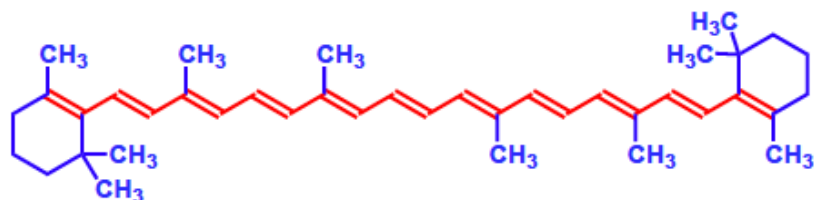
217

1,3,5-hexatriene

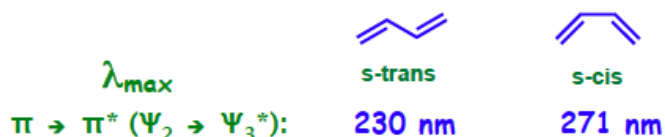
258

$\beta$ -Carotene

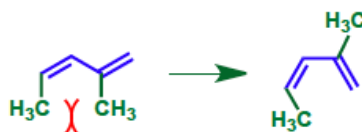
470



## Effect of s-cis & s-trans Conformers:

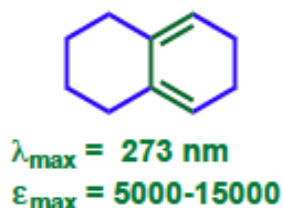
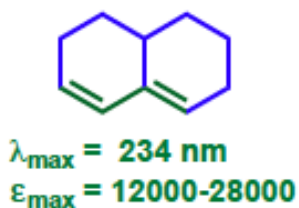


- Probably repulsion between terminal lobes of  $\Psi_2$  increases energy of HOMO ( $\Psi_2$ ) in s-cis form. Hence, less energy (ie. Higher wavelength) is required for  $\Psi_2 \rightarrow \Psi_3^*$  transition.



- Substitution may force a molecule to take s-cis form, therefore, absorbs energy from a longer wavelength (shows a red shift) than usual s-trans conformer.
- In cyclic system a double bond is forced to stay in s-cis (Cisoid) form, therefore, shows a red shift with a drop in intensity.

## Homoannular & Heteroannular Dienes:



## Woodward rules for calculation of wavelength values

- Woodward (1941) predicted  $\lambda_{\max}$  values only for the lowest energy transition ( $\pi \rightarrow \pi^*$ ) from HOMO to LUMO.

### Base values:

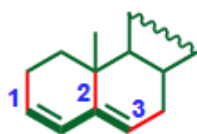
- |   |        |
|---|--------|
| ➤ Base value for an unsubstituted, conjugated, acyclic or heteroannular diene | 214 nm |
| ➤ Base value for an unsubstituted, conjugated, homoannular diene              | 253 nm |

### Increments for:

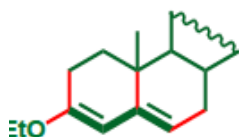
Each extra double bonds in conjugation	+ 30 nm
Exocyclic double bond (effect is two fold if the bond is exocyclic to two rings)	+ 5 nm

### Substituent effect:

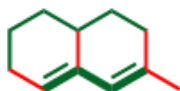
A. -OCOR or -OCOAr	+ 0 nm
B. Simple alkyl substituents or ring residue	+ 5 nm
C. Halogen (-Cl, -Br)	+ 5 nm
D. OR (R=Alkyl)	+ 6 nm
E. SR (R=Alkyl)	+ 30 nm
F. NR <sub>2</sub> (R=Alkyl)	+ 60 nm



Transoid (base):	214 nm
3 ring residues :	+15
1 exocyclic C=C:	+ 5
Total:	234 nm
Observed:	235 nm



Transoid (base):	214 nm
3 ring residues:	+15
1 exocyclic C=C:	+ 5
-OR:	+ 6
Total:	240 nm
Observed:	241 nm



Transoid (base):	214 nm
3 Ring residues:	+15
1 Alkyl substituent:	+ 5
1 Exocyclic C=C:	+ 5
Total:	239 nm

## Rules of Enone & Dienone Absorption

### Base values:

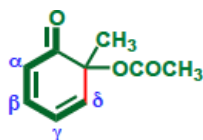
➤ Acyclic $\alpha,\beta$ -unsaturated ketones	215 nm
➤ 6-membered cyclic $\alpha,\beta$ -unsaturated ketones	215 nm
➤ 5-membered cyclic $\alpha,\beta$ -unsaturated ketones	202 nm
➤ $\alpha,\beta$ -unsaturated aldehydes	210 nm
➤ $\alpha,\beta$ -unsaturated carboxylic acid & esters	195 nm

### Increments for:

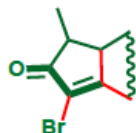
Double bond extending conjugation (DEC):	+30
Exocyclic double bond:	+ 5
Homodiene component:	+39

### Increments for:

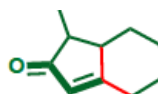
Alkyl group/ring residue: $\alpha$	+10
$\beta$	+12
$\gamma$ & higher	+18
Polar groups: -OH: $\alpha$	+35
$\beta$	+30
$\delta$	+50
-OAc: $\alpha,\beta,\gamma$	+ 6
-OMe: $\alpha$	+35
$\beta$	+30
$\gamma$	+17
$\delta$	+31
-SAlk: $\beta$	+85
-Cl: $\alpha$	+15
$\beta$	+12
-Br: $\alpha$	+25
$\beta$	+30
-NR <sub>2</sub> : $\beta$	+95



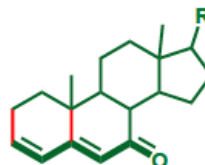
Base value:	215 nm
1 DEC:	+30
Homocyclic diene:	+39
δ ring residue:	+18
Total:	302 nm
Observed:	300 nm



Base value:	202 nm
1 α-Br:	+25
2 β-ring residue:	+24
Exocyclic C=C:	+ 5
Total:	256 nm
Observed:	251 nm



Base value:	202 nm
Exocyclic C=C:	+ 5
2 β-ring residues:	+24
Total:	231 nm
Observed:	226 nm



Base value:	215 nm
1 DEC:	+30
β-ring residue:	+12
δ ring residue:	+18
2 Exocyclic C=C:	+ 5
Total:	280 nm
Observed:	280 nm

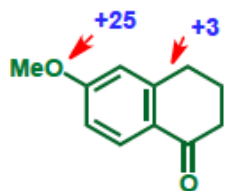
## Aromatic Compounds

Parent chromophore: Ar = C<sub>6</sub>H<sub>5</sub>

Ar-CO-R	246 nm
Ar-CHO	250 nm
Ar-COOH or Ar-COOR	230 nm

### Increment for each substituent on Ar:

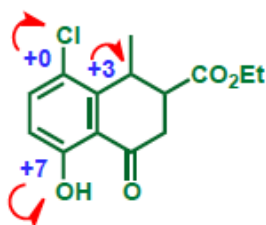
Alkyl or ring residue	<i>o, m</i>	+ 3 nm
	<i>p</i>	+ 10 nm
OH, OCH <sub>3</sub> , OAlk	<i>o, m</i>	+ 7 nm
	<i>p</i>	+ 25 nm
NH <sub>2</sub>	<i>o, m</i>	+ 13 nm
	<i>p</i>	+ 58 nm
NHCOCH <sub>3</sub>	<i>o, m</i>	+ 20 nm
	<i>p</i>	+ 45 nm
NHMe	<i>p</i>	+ 73 nm
NMe <sub>2</sub>	<i>o, m</i>	+ 20 nm
	<i>p</i>	+ 85 nm
Cl	<i>o, m</i>	+ 0 nm
	<i>p</i>	+ 10 nm
Br	<i>o, m</i>	+ 2 nm
	<i>p</i>	+ 15 nm



$$\text{Calc } \lambda_{\text{max}}^{\text{EtOH}} = 246 \text{ (parent chromophore)} + 3 \text{ (o-ring residue)} + 25 \text{ (p-OMe)}$$

$$= 274 \text{ nm}$$

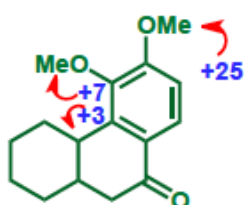
$$\text{Obs } \lambda_{\text{max}}^{\text{EtOH}} = 276 \text{ nm}$$



$$\text{Calc } \lambda_{\text{max}}^{\text{EtOH}} = 246 + 3 \text{ (o-ring residue)} + 7 \text{ (o-OH)}$$

$$= 256 \text{ nm}$$

$$\text{Obs } \lambda_{\text{max}}^{\text{EtOH}} = 257 \text{ nm}$$



$$\text{Calc } \lambda_{\text{max}}^{\text{EtOH}} = 246 + 25 + 7 + 3 = 281 \text{ nm}$$

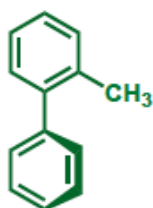
$$\text{Obs } \lambda_{\text{max}}^{\text{EtOH}} = 278 \text{ nm}$$

### Deviation from Woodward Rules

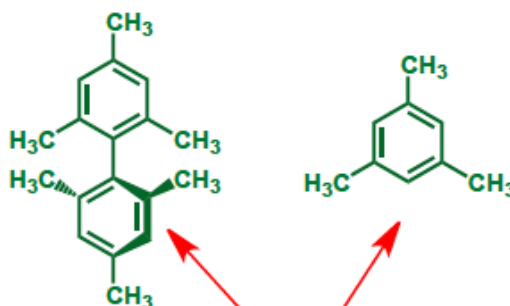
#### Biphenyls:



250 nm



237 nm

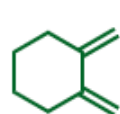


266 nm

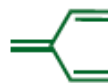
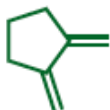
Not planar  
45 °C angle

Substitutions cause loss of co-planarity of orbitals.  
Loss of overlap, blue shift with reduced intensity.

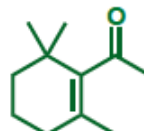
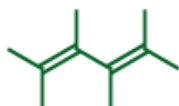
- (1) In alkenes, trans isomers exhibit absorption at longer wavelength and high intensity.
- (2) Woodward rules are applicable only if there is no strain around chromophore.



Ring strain



Cross conjugation



Steric inhibition of resonance

(3) If calculated and experimental values of  $\lambda_{\max}$  do not match, one can say that the molecule must have some strain.

(4) Thus UV can be used indirectly to determine if the molecule has any strain.

### Applications of UV Spectrophotometry

#### 1. Detection of Impurities

UV absorption spectroscopy is one of the best methods for determination of impurities in organic molecules. Additional peaks can be observed due to impurities in the sample and it can be compared with that of standard raw material. By also measuring the absorbance at specific wavelength, the impurities can be detected. Benzene appears as a common impurity in cyclohexane. Its presence can be easily detected by its absorption at 255 nm.

#### 2. Structure elucidation of organic compounds

UV spectroscopy is useful in the structure elucidation of organic molecules, the presence or absence of unsaturation, the presence of hetero atoms. From the location of peaks and combination of peaks, it can be concluded that whether the compound is saturated or unsaturated, hetero atoms are present or not etc.

#### 3. Quantitative analysis

UV absorption spectroscopy can be used for the quantitative determination of compounds that absorb UV radiation. This determination is based on Beer's law which is as follows.

$$A = \log I_0 / I_t = \log 1/T = -\log T = abc = \epsilon bc$$

Where  $\epsilon$  is extinction co-efficient,  $c$  is concentration, and  $b$  is the length of the cell that is used in UV spectrophotometer.

Other methods for quantitative analysis are as follows.

- a. calibration curve method
- b. simultaneous multicomponent method
- c. difference spectrophotometric method
- d. derivative spectrophotometric method

#### **4. Qualitative analysis**

UVabsorption spectroscopy can characterize those types of compounds which absorbs UV radiation. Identification is done by comparing the absorption spectrum with the spectra of known compounds. UV absorption spectroscopy is generally used for characterizing aromatic compounds and aromatic olefins.

#### **5. Dissociation constants of acids and bases.**

$$\text{pH} = \text{PKa} + \log \frac{[\text{A}^-]}{[\text{HA}]}$$

From the above equation, the PKa value can be calculated if the ratio of  $[\text{A}^-] / [\text{HA}]$  is known at a particular PH. and the ratio of  $[\text{A}^-] / [\text{HA}]$  can be determined spectrophotometrically from the graph plotted between absorbance and wavelength at different pH values.

#### **6. Chemical kinetics**

Kinetics of reaction can also be studied using UV spectroscopy. The UV radiation is passed through the reaction cell and the absorbance changes can be observed.

#### **7. Quantitative analysis of pharmaceutical substances**

Many drugs are either in the form of raw material or in the form of formulation. They can be assayed by making a suitable solution of the drug in a solvent and measuring the absorbance at specific wavelength.

Diazepam tablet can be analyzed by 0.5% H<sub>2</sub>SO<sub>4</sub> in methanol at the wavelength 284 nm.

#### **8. Molecular weight determination**

Molecular weights of compounds can be measured spectrophotometrically by preparing the suitable derivatives of these compounds.

For example, if we want to determine the molecular weight of amine then it is converted in to amine picrate. Then known concentration of amine picrate is dissolved in a litre of

solution and its optical density is measured at  $\lambda_{\text{max}}$  380 nm. After this the concentration of the solution in gm moles per litre can be calculated by using the following formula.

"c" can be calculated using above equation, the weight "w" of amine picrate is known. From "c" and "w", molecular weight of amine picrate can be calculated. And the molecular weight of picrate can be calculated using the molecular weight of amine picrate.

#### **9. As HPLC detector**

A UV/Vis spectrophotometer may be used as a detector for HPLC. The presence of an analyte gives a response which can be assumed to be proportional to the concentration. For more accurate results, the instrument's response to the analyte in the unknown should be compared with the response to a standard; as in the case of calibration curve.



# **Infra red spectroscopy: Basic Concept, absorption mechanism**

## **1. Introduction to IR Spectroscopy**

Spectroscopy can be defined as the interaction between matter and light. Infrared spectroscopy is a very powerful technique which uses electromagnetic radiation in the infrared region for the determination and identification of molecular structure as well as having various quantitative applications within analytical chemistry (Figure 1).

We do not aim to provide a mechano-quantic description of light and its interaction with atoms, as this is out of the scope of this module. However, it is important to note that atoms can absorb energy from electromagnetic radiation; this absorbed energy alters the state of the atoms within the molecule. These changes are usually manifest in alterations to the frequency and amplitude of molecular vibrations, which may be measured and plotted to produce an infrared spectrum.<sup>1-4</sup>

Infrared spectrometers use optical devices for dispersing and focusing electromagnetic radiation of IR frequency which is passed through the sample and any changes in absorbance measured against a reference beam.

There are three well defined IR regions (near, mid and far). The boundaries between them are not clearly defined and debate still persists, but broadly they are defined as:

- **Near infrared (12820-4000  $\text{cm}^{-1}$ ):** poor in specific absorptions, consists of overtones and combination bands resulting from vibrations in the mid-infrared region of the spectrum.
- **Mid-infrared (4000-400  $\text{cm}^{-1}$ ):** provides structural information for most organic molecules.
- **Far Infrared (400-33  $\text{cm}^{-1}$ ):** has been less investigated than the other two regions; however, it has been used with inorganic molecules.

The low energies, typically encountered within the infrared region, are not sufficient to cause electronic transitions; however, they are large enough to cause changes in the frequency and amplitude of molecular vibrations.

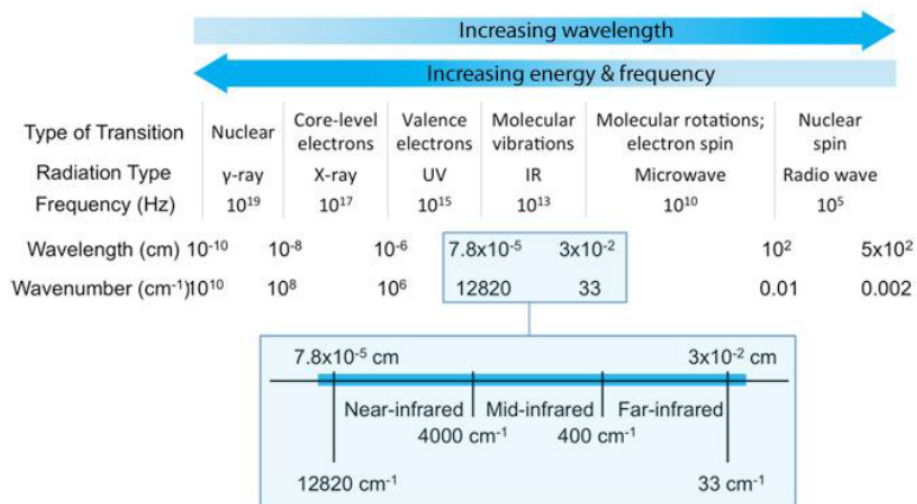


Figure 1: The electromagnetic spectrum and the infrared region.

## 2. Electromagnetic Spectrum

The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation, each of which can be considered as a wave or particle travelling at the speed of light, often referred to as a photon. These waves differ from each other in length and frequency.

**Frequency  $\nu$**  - the number of wave cycles that pass through a point in one second. Measured in Hertz (Hz).

**Wavelength  $\lambda$**  - The length of one complete wave cycle (cm).

Frequency and wavelength are inversely related (Equation 1):

$$\nu = \frac{c}{\lambda} \quad (1)$$

**Where:**

$c$  = speed of light  $3 \times 10^{10}$  cm/sec

The energy of a photon ( $E$  in Joules) is related to wavelength and frequency as follows (Equation 2):

$$E = h\nu = \frac{hc}{\lambda} \quad (2)$$

**Where:**

$h$  = Planck's constant  $6.6 \times 10^{-34}$  Joules-sec

Energy is directly proportional to frequency; therefore, high energy radiation will have a high frequency.

Energy is inversely proportional to wavelength, hence, short wavelengths are high energy and vice versa (Figure 2).

Type of Transition	Nuclear	Core-level electrons	Valence electrons	Molecular vibrations	Molecular rotations; electron spin	Nuclear spin
Radiation Type	$\gamma$ -ray	X-ray	UV	IR	Microwave	Radio wave
Frequency (Hz)	$10^{19}$	$10^{17}$	$10^{15}$	$10^{13}$	$10^{10}$	$10^5$
Wavelength (cm)	$10^{-10}$	$10^{-8}$	$10^{-6}$	$7.8 \times 10^{-5}$	$3 \times 10^{-2}$	$10^2$
Wavenumber ( $\text{cm}^{-1}$ )	$10^{10}$	$10^8$	$10^6$	12820	33	0.01

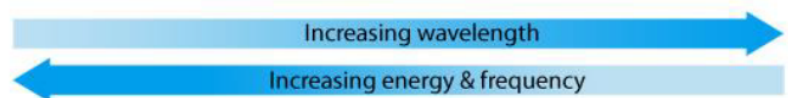


Figure 2: Electromagnetic spectrum.

### 3. Electromagnetic Radiation and Spectroscopy

The frequency and wavelength of electromagnetic radiation varies over many orders of magnitude. The electromagnetic spectrum is divided according to the type of atomic or molecular transition that gives rise to the absorption or emission of photons; UV, IR, microwave, radio wave etc. (Table 1).

Absorption spectroscopy relies on the absorption of energy from a photon which subsequently promotes the analyte from a lower-energy state to a higher-energy, or excited, state. As the energy of the photon changes the type of transition that the analyte undergoes will change. For example in IR spectroscopy, the absorption of relatively low IR radiation results in the vibration of chemical bonds within the analyte; a process which requires a fairly low energy input. Whereas, higher energy photons, such as those found in the UV-visible region of the electromagnetic spectrum, will promote valence electrons to move from their ground state to excited state energy levels within the atoms of an analyte; a process that requires a much greater energy input.

Increasing energy & frequency ↑	Type of Energy Transfer	Region of the Electromagnetic Spectrum	Spectroscopic Technique
	Absorption	γ-ray	Mossbauer
		X-ray	X-ray absorption
		UV-Vis	UV-Vis
			Atomic absorption
		Infrared	Infrared (IR)
			Raman
		Microwave	Microwave
			Electron spin resonance (EPR)
		Radio waves	Nuclear magnetic resonance (NMR)
	Emission (thermal excitation)	UV-Vis	Atomic emission
	Photoluminescence	X-ray	X-ray fluorescence
		UV-Vis	Fluorescence
			Phosphorescence
			Atomic fluorescence

Table 1: Electromagnetic spectrum region, type of energy transfer, and the associated spectroscopic technique.

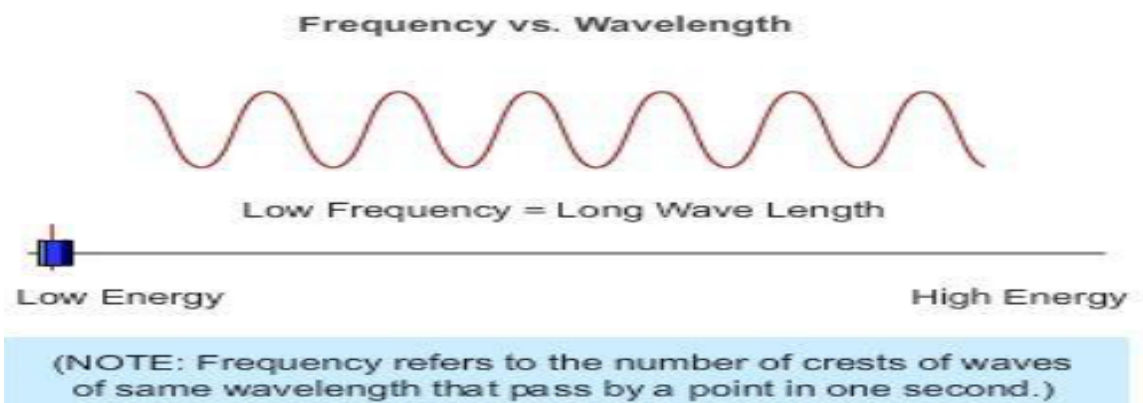


Figure 3: Relationship between frequency and wavelength.

#### 4. Infrared Regions

Infrared spectroscopy can be rationalized as the spectroscopy that deals with electromagnetic radiation of infrared frequency. As previously explained, there are three well defined infrared regions; each of them has the potential to provide different information: (Figure 4)

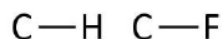
- **Far-Infrared ( $400\text{--}33\text{ cm}^{-1}$ ):** vibrations of molecules containing heavy atoms, molecular skeleton vibrations and crystal lattice vibrations
- **Mid-Infrared ( $4000\text{--}400\text{ cm}^{-1}$ ):** useful for organic analysis
- **Near Infrared ( $12820\text{--}4000\text{ cm}^{-1}$ ):** overtones; very useful for quantitative analysis

Infrared spectroscopy is one of the most useful and widely used methods to perform structural analysis.

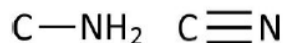
Given that the molecule under investigation is infrared active, (i.e. it absorbs Infrared radiation), then different types of structural information can be obtained.

Information achievable with Infrared spectroscopy includes:

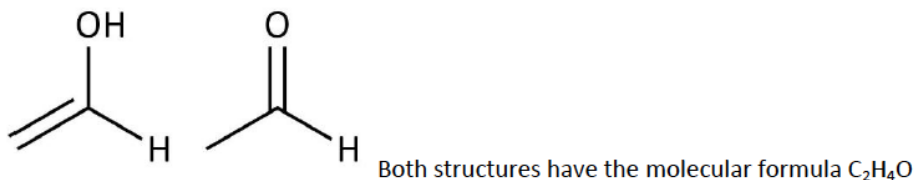
1. The type of atoms within the molecule.



2. The type of bonds between atoms.



3. The molecular structure. More often than not, infrared spectroscopy is insufficient to determine the complete structure and additional techniques (such as NMR, mass spectroscopy, etc.) are used to solve the puzzle.



4. From a quantitative point of view, infrared spectroscopy has a very well gained reputation for its power, flexibility, and reliability.

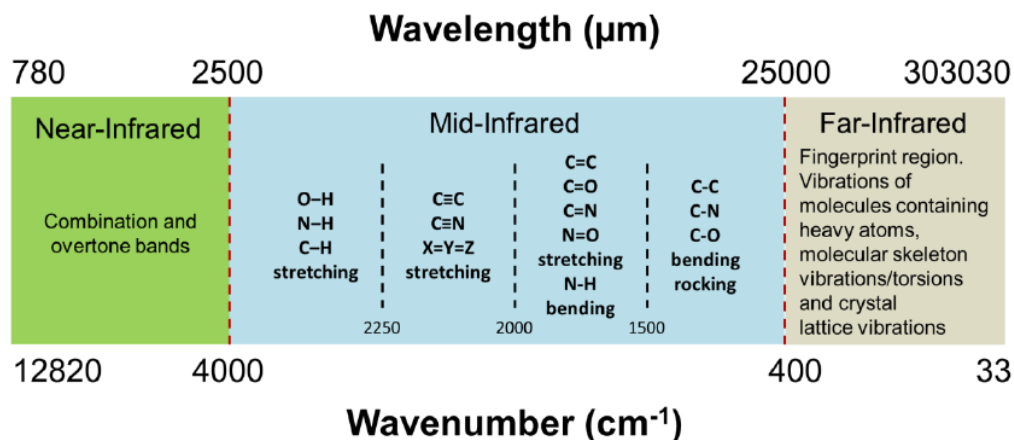
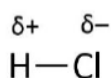


Figure 4: Infrared spectroscopy regions (oversimplified).

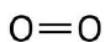
## 5. Molecular Vibrations

The absorption of light will increase both amplitude and frequency of molecular vibrations.<sup>4-5</sup> When the radiant energy matches the energy of a specific molecular vibration, absorption occurs. Molecules with a permanent dipole moment, such as water, HCl, and NO, are infrared active.

The HCl molecule possesses a permanent dipole moment, so it is infrared active.



The O<sub>2</sub> molecule does not possess a permanent dipole moment, so it is not infrared active.



In the case of alkenes (C=C) and alkynes (C≡C) if the bond is symmetrically substituted no band will be seen in the IR spectrum, however, if the bond is asymmetrically substituted a stretching frequency corresponding to the alkene or alkyne bond will be present (Table 2).

Oscillator	Wavenumber (cm <sup>-1</sup> )
C-H	3320-2700
-C=C-	1690-1590
C=O	1870-1590
C-O	1300-1050
C≡C	2250-2150
C-Cl	800-600

Table 2: Wavenumbers for selected diatomic oscillators.

In order to understand molecular vibrations, a bond can be treated as a simple harmonic oscillator composed of two masses (atoms) joined by a spring. Figure 6 depicts a diatomic molecule with two generic atoms (of masses  $m_1$  and  $m_2$ ) connected by a spring.



The classical vibrational frequency for a diatomic molecule (with force constant  $k$  and masses  $m_1$  and  $m_2$ ) has been derived from Hooke's Law (Equation 3):

$$\nu = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}} = \frac{1}{2\pi c} \sqrt{\frac{k(m_1 + m_2)}{m_1 m_2}} \quad (3)$$

**Where:**

$$\mu = \text{reduced mass} = \frac{m_1 m_2}{m_1 + m_2}$$

In terms of the wavenumber ( $\bar{\nu}$ ) (Equation 4):

$$\bar{\nu} = \frac{\nu}{c} = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}} = \frac{1}{2\pi c} \sqrt{\frac{k(m_1 + m_2)}{m_1 m_2}} \quad (4)$$

**Where:**

$c$  = speed of light =  $3 \times 10^{10}$  cm/sec

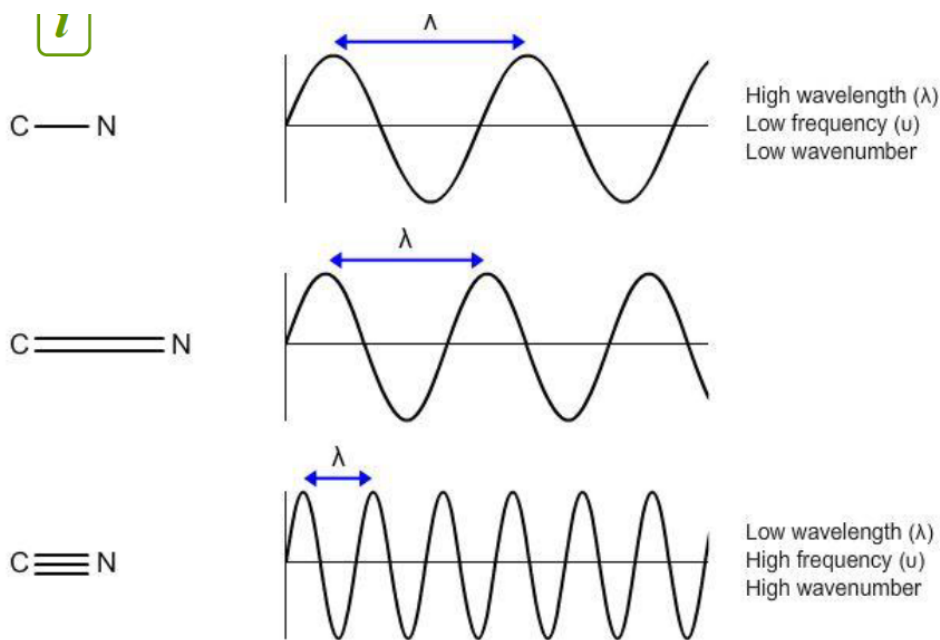


Figure 7: Comparison of wavelength, stretching frequency, and wavenumber of bonds with different strengths (i.e. single, double, and triple bonds).

## 7. Infrared Active Modes

A molecule that is infrared active must undergo a change in its dipole moment when vibrating. The simplest modes of vibration that are infrared active are stretching and bending modes (Figure 9).<sup>3-5</sup>

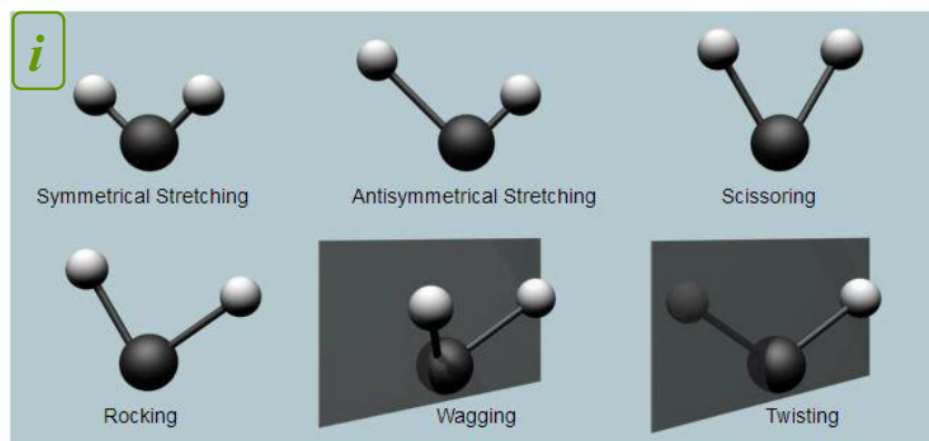
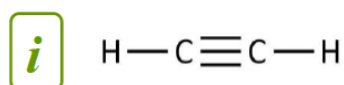


Figure 9: Modes of vibration (oversimplified).

For simplicity, we are going to illustrate the vibration modes in a linear molecule (acetylene in this case).



The symmetric  $\text{C}\equiv\text{C}$  stretching will not alter the acetylene's dipole moment and it is not infrared active.

However, substitution of either of the H atoms in acetylene produces an asymmetric alkyne bond which will be IR active.

Homonuclear diatomic molecules such as  $\text{Cl}_2$ ,  $\text{H}_2$ ,  $\text{N}_2$ , etc. will exhibit no infrared active modes as no change in their dipole moment is experienced during vibration.

Infrared (IR) radiation of all wavelengths is transmitted from the source. Some of the wavelengths of IR radiation will be absorbed by the sample and some of them will pass through (they are transmitted). The IR radiation which is transmitted is measured by the detector resulting in a unique IR spectrum for the sample of interest. This spectrum represents the IR absorption and transmission of that molecule. No two unique molecules will produce the same IR spectrum, resulting in IR spectroscopy being a very useful tool for molecular characterization and quantification.

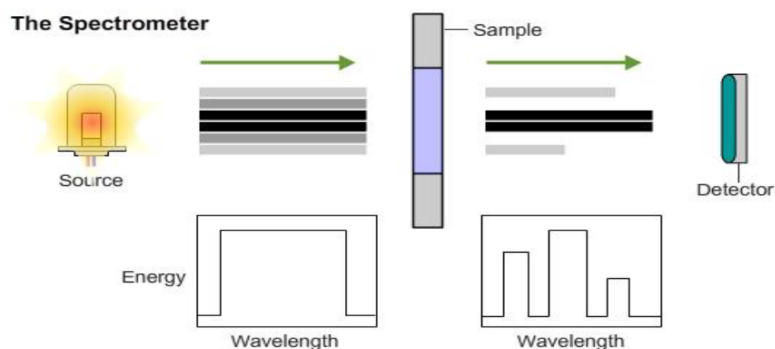


Figure 11: Sample absorption of IR radiation.



## 9. The IR Spectrum

Historically, infrared spectra have been represented as percent of transmittance versus either the wavenumber or the wavelength. The use of wavenumbers, is standard, with the use of wavelength (expressed in nm or  $\mu\text{m}$ ) having fallen out of favor.<sup>4-6, 8-10</sup>

In terms of wavenumbers the infrared region spans from 33 to 12820  $\text{cm}^{-1}$ . However, most infrared analyses are carried out in the mid-infrared region (400 to 4,000  $\text{cm}^{-1}$ ).

By convention, the wavenumbers are plotted in decreasing order from left to right. A typical IR spectrum is illustrated in Figure 12.

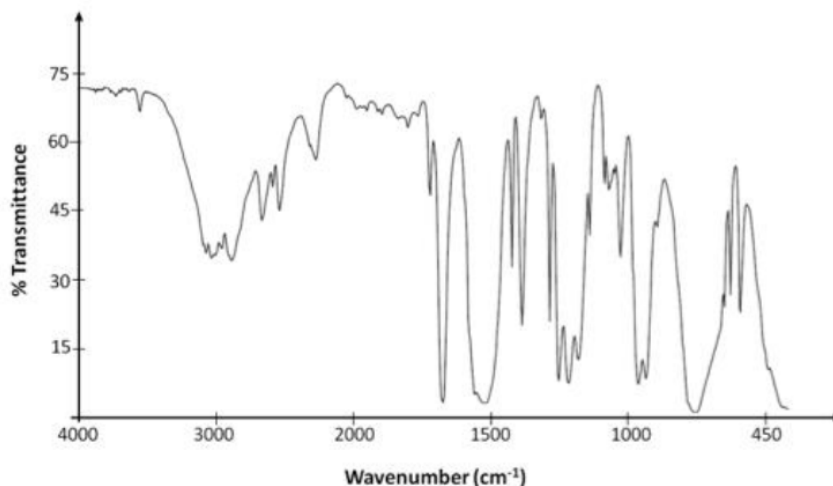
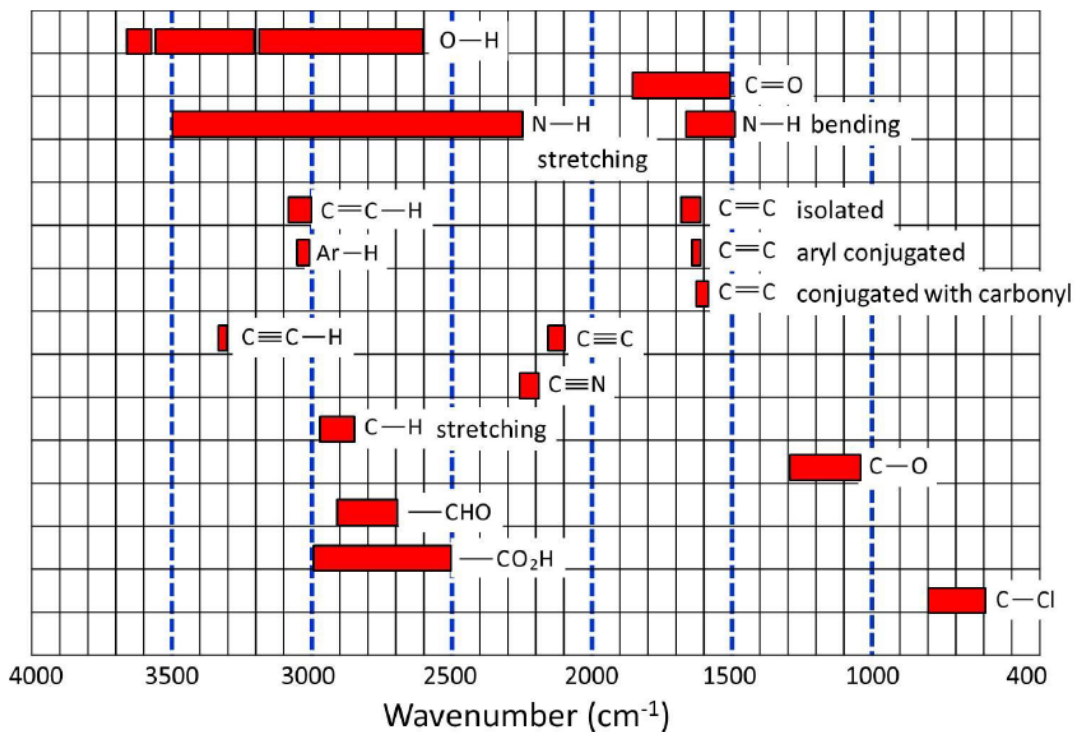


Figure 12: Typical IR spectrum.





## 11. Dispersive IR Instruments

Most IR spectrometers can be categorized into two classes: dispersive and Fourier Transform instruments.<sup>2-4</sup>

The basic design of a dispersive single beam instrument includes a source of infrared radiation, a monochromator, and the detector (Figure 13).

After interacting with the sample (or the blank), infrared radiation is dispersed by a monochromator into its individual frequency components and information on which frequencies were absorbed can be obtained using a photodiode array detector.

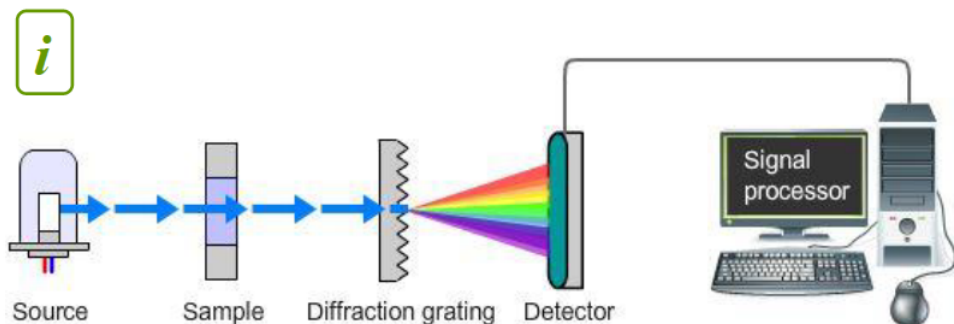


Figure 13: Basic concept of a single beam IR instrument.

Sources and detectors for infrared radiation have limited stability; with light intensity and detector sensitivity changing over time, or with fluctuations in temperature etc. The blank (reference or background) and sample measurements should be made one after the other to ensure they are made under the same analytical conditions. This limitation is minimized by the use of double beam instruments which are capable of measuring the sample and reference simultaneously.

Double beam instruments use 'choppers' to control the path of the radiation, alternating between the sample and the reference (Figure 14). These instruments use the known speed of rotation of the beam chopper to compare and resolve the information reaching the detector.

The use of an opaque surface provides the means for adjusting the 0% transmittance response of the detector.

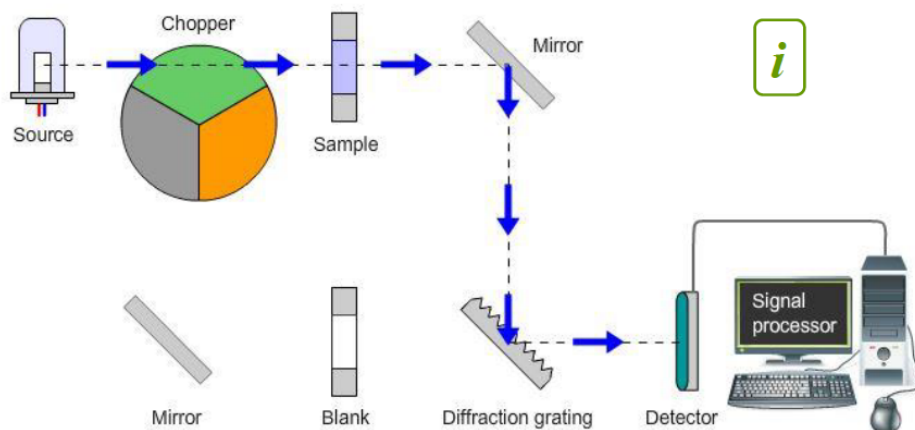


Figure 14: The double beam IR instrument.

## 12. FTIR Instruments

FTIR stands for Fourier Transform Infrared. FTIR spectrometers consist of an IR source, interferometer, sample cell or chamber, detector and a laser.<sup>7,9,11</sup> A schematic of an FTIR instrument is shown below (Figure 15).

### IR source

IR radiation is emitted from a glowing black body source. IR radiation passes through an aperture which controls the amount of radiation that reaches the sample, and therefore, the detector.

Common IR sources are:

1. Silicon carbide rods which are resistively heated and commonly known as a Globar. An electric current is passed through the rod which becomes very hot (1300 K) and emits large amounts of IR radiation. Previously, cooling with water was required to avoid damaging electrical components; however, advances in metal alloys have led to the production of Globars that do not require cooling by water.
2. Nichrome and Kanthal wire coils were once popular IR sources and did not require cooling as they ran at lower temperatures than Globars, however, this also resulted in lower amounts of IR radiation being emitted.
3. Nernst Glowers are manufactured from a mixture of refractory oxides and are capable of reaching hotter temperatures than a Globar; however, they are not capable of producing IR radiation above  $2000\text{ cm}^{-1}$ .

### Interferometer

The first interferometer was invented by Albert Abraham Michelson, who received a Nobel Prize for his work in 1907. Without this essential piece of optical equipment the modern day FTIR system would not exist. The interferometer consists of a beam splitter, a fixed mirror, and a moving mirror.

### Beam Splitter

The beam splitter is made of a special material which transmits half of the incident radiation and reflects the other half. IR radiation from the source strikes the beam splitter and is separated into two beams. One beam is transmitted through the beam splitter to the fixed mirror while the other beam is reflected from the beam splitter to the moving mirror. Both mirrors reflect the radiation back to the beam splitter where the two beams interfere to produce an interferogram.

### Moving Mirror

The moving mirror is a flat highly reflective surface mounted on air bearings that allow for high speed movement of the mirror (movements are made once every millisecond). The moving mirror only moves a few millimeters away from the beam splitter.

### Fixed Mirror

The fixed mirror is a flat highly reflective surface.

## FTIR Advantages

FTIR instruments have several advantages over dispersive IR instruments including:

### Speed

All IR frequencies are measured simultaneously, resulting in measurements being taken in seconds rather than minutes. This is often referred to as the Fellgett Advantage.

### Sensitivity

The detectors utilized in FTIR instruments are highly sensitive which results in lower signal to noise ratios. This is known as the Fellgett Advantage.

### Simplicity

The only moving part in an FTIR instrument is the mirror in the interferometer; therefore, there is very little need for mechanical maintenance.

### Internal calibration

The internal laser is used to self-calibrate the moving mirror in the FTIR instrument negating any need for timely or complicated external calibration. This is denoted as the Fellgett Advantage.

## 2.3 FACTORS INFLUENCING VIBRATIONAL FREQUENCIES

Many factors influence the precise frequency of a molecular vibration, and it is usually impossible to isolate one effect from another. For example, the  $\text{C}=\text{O}$  *str* frequency in the ketone  $\text{RCOCH}_3$  is lower than in  $\text{RCOCl}$ ; is the change in frequency of the  $\text{C}=\text{O}$  *str* due to the difference in *mass* between  $\text{CH}_3$  and  $\text{Cl}$ , or is it associated with the *inductive* or *mesomeric* influence of  $\text{Cl}$  on the  $\text{C}=\text{O}$  bond; perhaps there is some *coupling* interaction between the  $\text{C}=\text{O}$  and  $\text{C}-\text{Cl}$  bonds, or is there some steric effect which alters the *bond angles*?

We shall discuss here frequency shifts, which are brought about by structural changes in the molecule, or by interaction between functional groups. Due emphasis will be placed on those features that are most valuable in explaining the characteristic appearance and positions of the group frequencies.

Primary mass effects (for example, the mass effect of changing  $\text{C}-\text{H}$  to  $\text{C}-\text{Cl}$ ) have been mentioned in section 2.2; secondary mass effects (for example, the effect on  $\text{C}=\text{O}$  *str* of changing  $\text{CO}-\text{CH}_3$  to  $\text{CO}-\text{Cl}$ ) are very difficult to study, because of the unavoidable intrusion of electronic effects. Frequency shifts also take place on moving from condensed phases to dilute solutions, as mentioned in the section on sampling techniques (see section 2.5).

### 2.3.1 VIBRATIONAL COUPLING

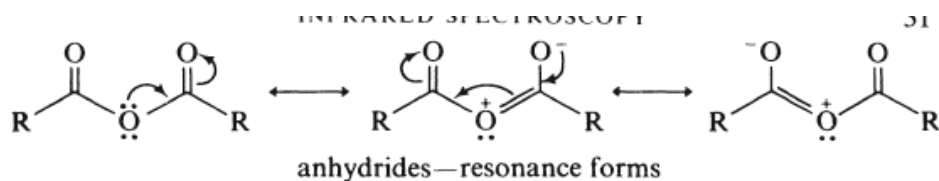
An isolated  $\text{C}-\text{H}$  bond has only one stretching frequency, but the stretching vibrations of  $\text{C}-\text{H}$  bonds in  $\text{CH}_2$  groups combine together to produce two *coupled vibrations* of different frequencies—the antisymmetric,  $\bar{\nu}_{\text{anti}}$ , and symmetric,  $\bar{\nu}_{\text{sym}}$ , combinations discussed earlier and illustrated in figure 2.5. The  $\text{C}-\text{H}$  bonds in  $\text{CH}_3$  groups also give rise to symmetric and antisymmetric vibrations. These are of different frequencies from those of  $\text{CH}_2$  groups, and all four vibrations can be seen in

high-resolution spectra of compounds containing both  $\text{CH}_2$  and  $\text{CH}_3$  groups.

Vibrational coupling takes place between two bonds vibrating with similar frequency, provided that the bonds are reasonably close in the molecule; the coupling vibrations *may both be fundamentals* (as in the coupled stretching vibrations of  $\text{AX}_2$  groups) or a *fundamental vibration may couple with the overtone* of some other vibration. This latter coupling is frequently called Fermi resonance, after Enrico Fermi, who first described it.

Vibrational coupling is a feature of other  $\text{AX}_2$  groups, so that the functions listed in table 2.1 exhibit not one, but two, stretching bands—antisymmetric and symmetric  $\text{A—X str}$  (antisymmetric usually being of higher frequency).

*Carboxylic acid anhydrides.* These give rise to two  $\text{C=O str}$  absorptions,  $\bar{\nu}_{\text{anti}}$  and  $\bar{\nu}_{\text{sym}}$  (around  $1800\text{--}1900\text{ cm}^{-1}$ , with a separation of about  $65\text{ cm}^{-1}$ ); coupling occurs between the two carbonyl groups, which are *indirectly* linked through  $\text{—O—}$ : the interaction is presumably encouraged because of the slight double-bond character in the carbonyl-oxygen bonds brought about by resonance, since this will keep the system coplanar. The high-frequency band in this case is the symmetric  $\text{C=O str}$ .



*Amides.* These show two absorption bands around  $1600\text{--}1700\text{ cm}^{-1}$  corresponding mainly to  $\text{C=O str}$  and  $\text{N—H def}$ , but because of vibrational coupling, the original characters of the vibrations are modified. The two bands are not pure  $\text{C=O str}$  and  $\text{N—H def}$ , and are usually referred to as the amide I and amide II bands. Amide I may be as high as 80 per cent  $\text{C=O str}$  in character, but amide II is a strongly coupled interaction between  $\text{N—H def}$  and  $\text{C—N str}$ . (See also section 2.9.)

In *aldehydes* the  $\text{C—H str}$  absorption usually appears as a doublet because of interaction between the  $\text{C—H str}$  fundamental and the overtone of  $\text{C—H def}$ .

### 2.3.2 HYDROGEN BONDING

Hydrogen bonding, especially in  $\text{O—H}$  and  $\text{N—H}$  compounds, gives rise to a number of effects in infrared spectra, and its importance here can scarcely be overemphasized. While most routine organic work will involve relatively nonassociating solvents ( $\text{CCl}_4$ ,  $\text{CS}_2$ ,  $\text{CHCl}_3$ ), more polar solvents such as acetone or benzene will certainly influence  $\text{O—H}$  and  $\text{N—H}$  absorptions. Carbonyl groups or aromatic rings *in the same molecule* as the

O—H or N—H group may cause similar shifts by intramolecular action.

*Alcohols and phenols.* Figure 2.6 shows the infrared spectrum of an alcohol (1-butanol) recorded as a liquid film; the dotted line insert around  $3500\text{ cm}^{-1}$  was recorded in dilute solution (about 1 per cent in  $\text{CCl}_4$ ). At low concentrations a sharp band appears at  $3650\text{ cm}^{-1}$  in addition to the broad band at  $3350\text{ cm}^{-1}$ .

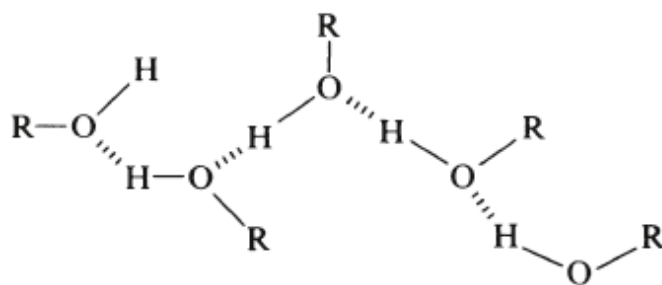
The sharp band is O—H *str* in *free* alcohol molecules; the broad band is O—H *str* in hydrogen-bonded alcohol molecules.

Alcohols in phenols in condensed phases (bulk liquid or KBr disks, etc.) are strongly hydrogen-bonded, usually in the form of a dynamic polymeric association; dimers, trimers and tetramers also exist, and this leads to a wide envelope of absorptions and, hence, to broadening of the absorption band. In dilute solution in inert solvents (or in the vapor phase) the proportion of free molecules increases and these give rise to the  $3650\text{ cm}^{-1}$  band.

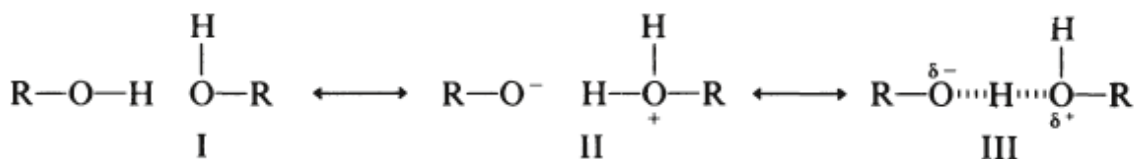
Is it reasonable that bonded O—H *str* should appear at lower frequency than free O—H *str*?

The hydrogen bond can be regarded as a resonance hybrid of I and II (approximating overall to III), so that hydrogen bonding involves a lengthening of the original O—H bond. This bond is consequently

weakened (that is, its force constant is reduced), so the stretching frequency is lowered.



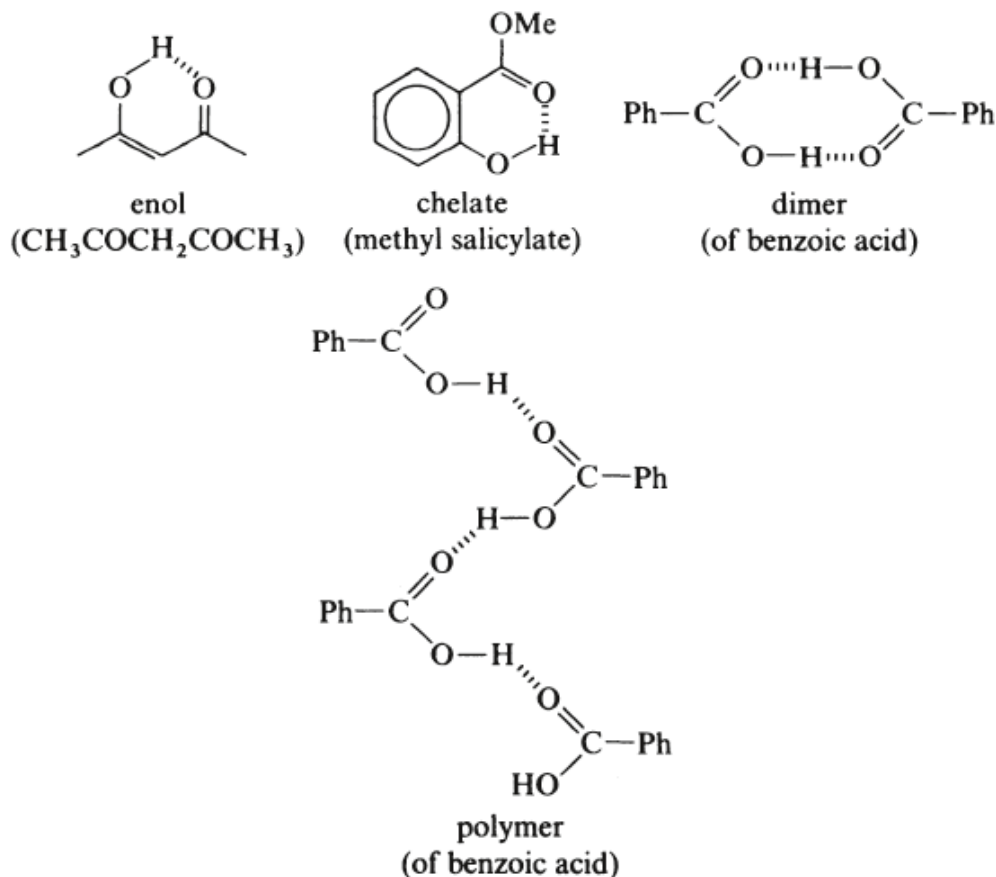
polymeric association of O—H compounds



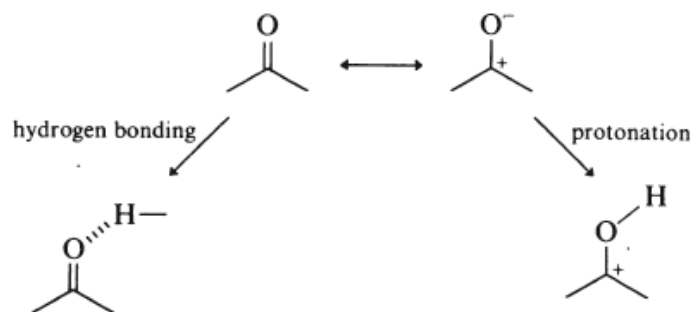
lengthening of O—H bond in hydrogen bonding



*Enols and chelates.* Hydrogen bonding in enols and chelates is particularly strong, and the observed O—H *str* frequencies may be very low (down to  $2800\text{ cm}^{-1}$ ). Since these bonds are not easily broken on dilution by an inert solvent, free O—H *str* may not be seen at low concentrations.



*Carbonyl compounds.* In enols and in chelates such as methyl salicylate hydrogen bonding will influence not only the O—H vibration frequency but also the C=O vibration to which it hydrogen-bonds. The key factor here is the basicity of the C=O group: the more basic it is, the stronger will be the hydrogen bond that it can form. The extreme case of



protonation shows that the C=O bond has increased single-bond character and longer length: the same tendency occurs in hydrogen bonding, leading to a lowering of the vibration frequency.

*Carboxylic acids.* Figure 2.7 shows the infrared spectrum of benzoic acid, and the exceedingly broad band reaching from  $2500\text{ cm}^{-1}$  to  $3500\text{ cm}^{-1}$  is hydrogen-bonded O—H *str*. We are seeing here the O—H *str* band for the carboxylic acid *dimer* structure: in condensed phases, all carboxylic acids exist in this stable *dimeric association* in which the hydrogen bonds are particularly strong. (The fine structure on the O—H *str* peak is usually attributed to vibrational coupling with overtones of lower frequencies.) In very dilute solution in hexane it is just possible to distinguish free O—H *str*, but this is extreme dilution. Even in  $\text{CCl}_4$  some degree of hydrogen bonding to solvent arises and in extreme dilution in  $\text{CCl}_4$  the free O—H *str* absorption is seen at lower frequency than in hexane. Polymeric association is also known to occur in carboxylic acids, although dimeric association is the norm; the proportion of monomer to dimer increases in solvents such as benzene, and in dioxan there is no dimer formed, since the acid hydrogen-bonds preferentially to the solvent.

*$\pi$ -Cloud interactions.* Since alkene and aromatic  $\pi$  bonds can behave as Lewis bases, it is not surprising that they can form hydrogen bonds to acidic hydrogens; the frequency of O—H *str* in phenols can be lowered by  $40\text{--}100\text{ cm}^{-1}$  when the spectrum is recorded in benzene solution, compared with carbon tetrachloride solution.

*Amines.* In condensed phase spectra amines show bonded N—H *str* around  $3300\text{ cm}^{-1}$  and in dilute solution a new band near  $3600\text{ cm}^{-1}$  corresponds to free N—H *str*. Since nitrogen is less electronegative than oxygen, hydrogen bonds in amines are weaker than in alcohols, and the shifts in frequency are also correspondingly less dramatic than in alcohols.

### 2.3.3 ELECTRONIC EFFECTS

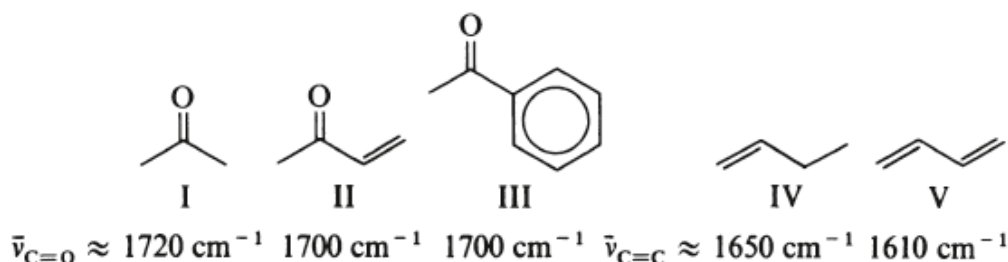
One can use the theoretical principles of the organic chemist to explain many of the frequency shifts that occur in vibrations when the substituents are altered. The expected *inductive* and *mesomeric* (or *resonance*) effects are seen to be at work, together with an occasional through-space influence (or *field effect*).

Many unresolved problems remain, however, and we cannot concentrate on successes and ignore the many instances where simple theory fails to offer a reasonable explanation. Vibrational coupling (see section 2.3.1) often means that an observed absorption band is *not* purely associated with one bond alone and this will complicate our explanations; most C—H *def* modes are coupled vibrations, and we have seen that C=O *str* is a coupled vibration in amides and anhydrides, and is also a coupled vibration in such simple compounds as benzoyl chloride and cyclopentanone.

Again, if we examine the series MeOH, PhOH, MeCOOH, we find that the O—H *str* frequency decreases, while in the series MeNH<sub>2</sub>, PhNH<sub>2</sub>, MeCONH<sub>2</sub> the N—H *str* frequency inexplicably increases. We must also consider the effect of electronic influences on the strengths of the bonds *adjacent* to the bond whose frequency we are measuring: thus, pictorially, if we stiffen up the bonds to a C=O group, we will make it more difficult for the carbonyl carbon atom to move, and all of the vibration amplitude will have to be taken up by the oxygen atom, with almost inevitable shift in the C=O *str* frequency (see section 2.3.4).

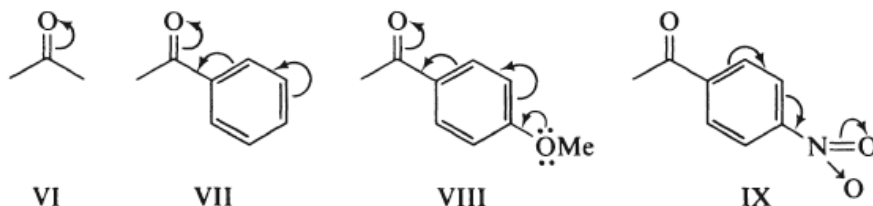
With caution in mind, we can now look at cases where theory has been successful in explaining frequency shifts.

*Conjugation lowers* the frequency of C=O *str* and C=C *str*, whether the conjugation is brought about by αβ unsaturation or by an aromatic ring. Compare I with II and III; or compare IV with V.



The explanation of this shift is similar for C=O and C=C, but we shall illustrate it in relation to the C=O bond in III. In III delocalization of π electrons between C=O and the ring increases the double-bond character of the bond joining the C=O to the ring. This leads to a lower bond order in the C=O bond, which is consequently weakened; the decrease in force constant lowers the stretching vibration frequency by 20–30 cm<sup>-1</sup>.

One can also attribute such C=O frequency shifts to the mesomeric (or resonance) effect: any substituent that enhances the mesomeric shift will decrease the bond order of the C=O bond and lead to lower C=O *str*

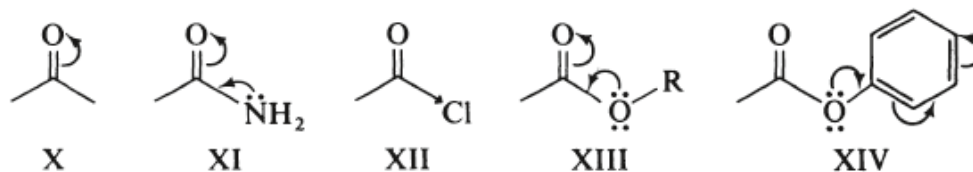


frequency. Conjugation with phenyl (in VII) does so, and a +M group such as *p*-MeO in VIII will lead to even lower frequencies. A *p*-NO<sub>2</sub> group (–M) will oppose these trends and lead to higher frequencies (as in IX).

*Inductive effects* are difficult to consider in isolation from mesomeric effects: in some molecules I is more important than M, while in others the reverse is true.



In amides, XI, the +M effect produces a lengthening (weakening) of the C=O bond, leading to lower frequency than in the corresponding ketone, X: the -I effect of nitrogen is here being dominated by +M. In contrast, the -I effect of chlorine in acyl chlorides, XII, is more influential than +M, and here an opposite shift (to higher frequency) occurs.



Esters represent another example of the conflict between I and M effects. In alkyl esters, XIII, the nonbonding electrons on oxygen increase the +M conjugation, tending to lower the C=O frequency. The electronegativity of oxygen, -I, operates in the opposite sense, but +M is apparently dominant. In phenyl esters, XIV, however, the nonbonding electrons are partly drawn into the ring, and their conjugation with C=O is consequently diminished. When this happens, the -I effect of oxygen becomes dominant, and C=O moves to higher frequency.

In examples such as these it is easier to rationalize the shifts than it is to predict them, and caution should be exercised in applying the rules to new situations. The importance of vibrational coupling requires constant re-statement.

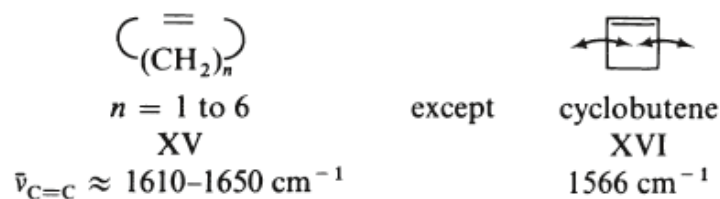
#### 2.3.4 BOND ANGLES

In *ketones*, the correlation charts show that highest C=O frequencies arise in the strained cyclobutanones, and we can explain this in terms of bond-angular strain: the C—CO—C bond angle is reduced below the normal 120°, leading to increased s character in the C=O bond. The

C=O bond is shortened and therefore strengthened and so  $\nu_{\text{C=O}}$  increases. If the bond angle is pushed outwards above 120°, the opposite effect operates, and for this reason di-*tert*-butyl ketone has a very low  $\bar{\nu}_{\text{C=O}}$  (1697 cm<sup>-1</sup>).

An alternative view involves no change in the C=O force constant, but merely an increased rigidity in the C—CO—C bond system as ring size decreases: C=O stretching must in these circumstances couple more effectively with C—C stretching, leading to higher C=O *str* frequencies.

*Cycloalkenes* also show such an effect, but a less simple relationship holds. Thus, in cycloalkenes, XV,  $\bar{\nu}_{\text{C=C}}$  falls with increasing strain, but reaches a minimum in cyclobutene. In cyclobutene, XVI, stretching of C=C involves only *bending* of the attached C—C bonds: in all the others (where the internal angles are not 90°) C=C stretching must involve some stretching of the adjacent C—C bonds, which involves increasing the energy (frequency) of C=C *str*.



C—H *stretching* vibrations move to higher frequency in the sequence alkane–alkene–alkyne. As hybridization goes from  $sp^3$  to  $sp^2$  to  $sp$ , the  $s$  character of the C—H bond increases; bond lengths become shorter, and frequencies rise. Cyclopropanes have high C—H *str* frequencies for the same reason (typical values being  $3040\text{--}3070 \text{ cm}^{-1}$ ): the C— $\hat{C}$ —C bond angle is substantially contracted below the normal  $109.5^\circ$ , leading to increased  $s$  character in the C—H bonds, and thus to higher frequencies.

### 2.3.5 FIELD EFFECTS

Two groups often influence each other's vibrational frequencies by a through-space interaction, which may be electrostatic and/or steric in nature. The best examples of this *field effect* are interactions between carbonyl groups and halogen atoms; for example, in the  $\alpha$ -chloroketone derivatives of steroids, XVII, C=O *str* frequency is higher when Cl is equatorial than when it is axial. Presumably the nonbonding electrons of oxygen and chlorine undergo repulsion when they are close together in the molecule; this results in a change in the hybridization state of oxygen, and therefore a shift in C=O *str* frequency.

In *o*-chlorobenzoic acid esters this field effect shifts the C=O frequency in the rotational isomer XVIII, and not in the isomer XIX; both isomers are normally present, so that *two* C=O *str* absorptions are observed in the spectrum of this compound.

## 2.6 APPLICATIONS OF INFRARED SPECTROSCOPY—IDENTITY BY FINGERPRINTING

Infrared spectra contain many absorptions associated with the complex interacting vibrating systems in the molecule, and this pattern of vibrations, since it is uniquely characteristic of each molecule, gives rise to a uniquely characteristic set of absorption bands in the spectrum.

This band pattern serves as a *fingerprint* of the molecule; the region that contains a particularly large number of unassigned vibrations (and is most valuable in this respect) is roughly from  $900 \text{ cm}^{-1}$  to  $1400 \text{ cm}^{-1}$ , and this general area is often called the *fingerprint region*.

To identify an unknown compound, one need only compare its infrared spectrum with a set of standard spectra recorded under identical conditions.

*Substances that give the same infrared spectra are identical.*

This proof of identity is far more characteristic than the comparison of any other physical property.

Having stated the principle, a few cautionary words should be added. For two spectra to be really identical would involve recording the spectra on the same machine under identical conditions of sampling, scan speed, slit widths, etc. Where this condition does not apply, some discretion must be allowed, but, in general, the greater the number of peaks in the fingerprint region the more reliable the proof of identity.

Digitized infrared spectra lend themselves very well to automatic computer library searching (see section 1S.1), and large compilations of spectra are held by many industrial companies: Sadtler Research Laboratories publish collections of infrared spectra in digital form for use by

individuals and institutions on their own computers. Even if big enough computers existed which were able to store the spectra from all known compounds (and there are about seven million, increasing by a quarter of a million each year), a library search could never determine the structure of a new unknown compound; at best, it could print out those stored spectra which have similar features to those of the unknown, but the chemist would thereafter have to interpret this information in conjunction with other data before a structure could be deduced.

Small changes in large molecules may produce very little change in the spectrum. For example, the infrared spectrum of a  $C_{20}$  straight-chain alkane is quite indistinguishable from that of its next higher straight-chain homolog. For a distinction of this magnitude, mass spectrometry would be the method of choice (see chapter 5).

## 2.7 APPLICATIONS OF INFRARED SPECTROSCOPY— IDENTIFICATION OF FUNCTIONAL GROUPS

By examining a large number of compounds known to contain a functional group, we can establish which infrared absorptions are associated with that functional group; we can also assess the range of frequencies within which each absorption should appear. Exactly this kind of information is set out in the *correlation charts* which follow (pp. 60–71).

Now, working in the converse, if we have an unknown compound whose functional groups we wish to identify, we can examine its infrared spectrum and use the correlation data to deduce which are the functional groups present.

It is impossible to arrive at a wholly systematic method for dealing with an infrared spectrum. All other evidence should be assessed simultaneously, be it chemical, physical or spectroscopic; even the known history of the compound can be revealing. It is *not* possible to identify a compound merely by interpreting its infrared spectrum from correlation data.

We shall discuss in detail the strengths and weaknesses of the method in the following pages, but it is useful now to make a few clear statements on the general principles involved.

(i) Most weight can be placed on the absorptions above  $1400\text{ cm}^{-1}$  and below  $900\text{ cm}^{-1}$ . (The fingerprint region,  $900\text{--}1400\text{ cm}^{-1}$ , contains many unassigned absorptions.)

(ii) *Group frequencies* are more valuable than single absorption bands. In other words, a functional group that gives rise to *many* characteristic absorptions can usually be identified more definitely than a function that gives rise to only one characteristic absorption. (Thus, ketones ( $C=O\text{ str}$ ) are less easily identified than esters ( $C=O\text{ str}$  and  $C-O\text{ str}$ ); esters are



less easily identified than amides ( $\text{C}=\text{O}$  *str*,  $\text{N}-\text{H}$  *str*,  $\text{N}-\text{H}$  *def*); etc.)

(iii) The absence of a characteristic absorption may be more illuminating than its presence. (Consider the relative implications of the presence or absence of a  $\text{C}=\text{O}$  *str* absorption.)

(iv) Multifunctional compounds will show the separate absorptions of the individual functional groups, unless these interact. (Examples of *interacting functional types* are  $\beta$ -diketones, aliphatic amino acids,  $\gamma$ -hydroxy acids, etc.)

(v) The frequencies shown graphically on the correlation charts do not take account of any exceptional features in specific molecules; important circumstances, which might in this way lead to frequency shifts outside the quoted ranges, are discussed below.

(vi) *Graphically presented correlation charts are invariably sufficiently accurate for functional group identification*; coupled with this, frequencies of bands cannot easily be measured more accurately than  $\pm 5\text{ cm}^{-1}$  on low-cost routine instruments (with lesser accuracy at higher frequencies).

More accurate tabular data are to be found in the specialist texts of Bellamy, Cross and van der Maas, and such tables should be used for studying the restricted frequency ranges of more narrowly specific classes of organic molecule. The discussions of group frequencies that follow contain some more detailed frequency data (see sections 2.8–2.13).

A reasonable initial plan of attack on the infrared spectrum of a totally unknown compound would be to spend a few minutes searching out the most commonly successful correlations.

The *carbon skeleton* should be tackled first (see section 2.8): look for evidence of alkane, alkene, alkyne and aromatic residues (using  $\text{C}-\text{H}$  *str*,  $\text{C}-\text{H}$  *def* and the various carbon-carbon bond stretching frequencies). Evidence from the NMR spectrum is of great complementary value.

Look for  $\text{C}=\text{O}$  *str*; if present, it may be associated with  $\text{C}-\text{H}$  *str* in aldehydes,  $\text{N}-\text{H}$  *str* in amides,  $\text{C}-\text{O}$  *str* in esters; etc.

Look for  $\text{O}-\text{H}$  *str* or  $\text{N}-\text{H}$  *str*.

Look for  $\text{C}\equiv\text{N}$  *str*.

In sulfur compounds look for  $\text{S}-\text{H}$  *str*,  $\text{S}=\text{O}$  *str* and  $-\text{SO}_2-$  *str*.

In phosphorus compounds look for  $\text{P}=\text{O}$  *str*.

Chemical and/or mass spectrometric evidence for the presence of nitrogen, sulfur, halogens or phosphorus, etc., is essential: infrared evidence of these is self-sufficient *only* in exceptional cases.

The correlation charts are set out in the order indicated by the above approach to an infrared identification of functional groups. Thus, 'aromatic carbon skeletons' precede alkane, since the former are frequently easier to confirm. The charts themselves contain commentary, which will frequently suffice to make an assignment, but additional discussion of each class is given after the charts.

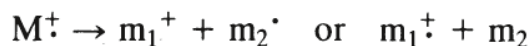
*The frequency ranges shown on the charts apply to spectra recorded on liquid films or KBr disks, or Nujol mulls, etc., since most routine spectra will be recorded thus. Where dilute solution spectra produce substantial shifts, this is indicated on the charts and in the discussion following.*

### **Mass spectrometry: Basic concepts, mass spectrometers, ionization techniques**

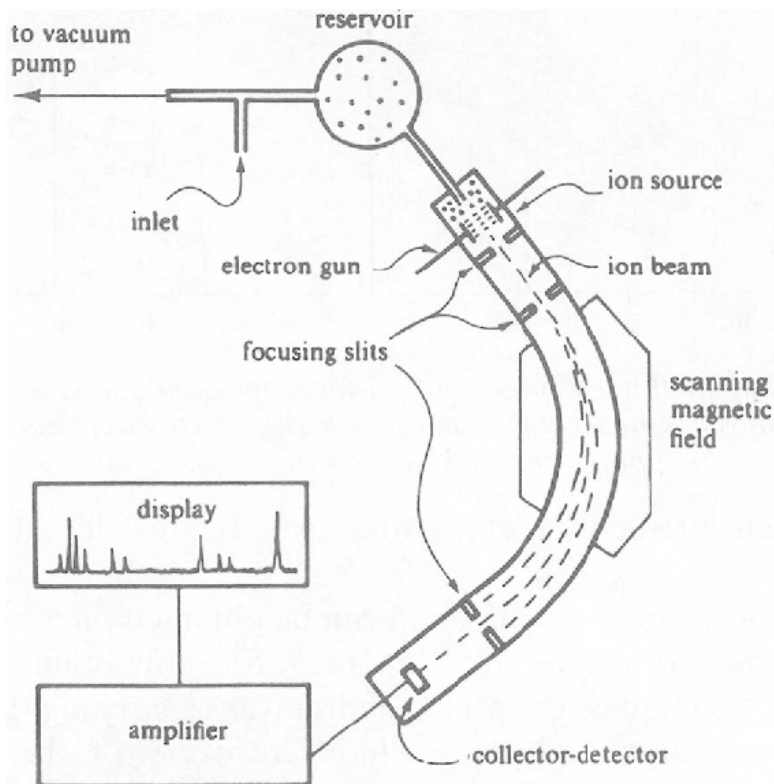
Organic chemists use mass spectrometry in three principal ways: (1) to measure *relative molecular masses* (molecular weights) with very high accuracy; from these can be deduced exact molecular formulae: (2) to detect within a molecule the places at which it *prefers to fragment*; from this can be deduced the presence of recognizable groupings within the molecule: and (3) as a method for identifying analytes by comparison of their mass spectra with libraries of digitized mass spectra of known compounds.

#### **Basic concepts**

In the simplest mass spectrometer (figure 5.1), organic molecules are bombarded with electrons and converted to highly energetic positively charged ions (*molecular ions* or *parent ions*), which can break up into smaller ions (*fragment ions*, or *daughter ions*); the loss of an electron from a molecule leads to a radical cation, and we can represent this process as  $M \rightarrow M^{\cdot+}$ . The molecular ion  $M^{\cdot+}$  commonly decomposes to a pair of fragments, which may be either a radical plus an ion, or a small molecule plus a radical cation. Thus,



The molecular ions, the fragment ions and the fragment radical ions are separated by deflection in a variable magnetic field according to their mass and charge, and generate a current (the *ion current*) at the collector in proportion to their *relative abundances*. A *mass spectrum* is a plot of relative abundance against the ratio mass/charge (the *m/z* value). For singly charged ions, the lower the mass the more easily is the ion deflected in the magnetic field. Doubly charged ions are occasionally formed: these are deflected twice as much as singly charged ions of the same mass, and they appear in the mass spectrum at the same value as do singly charged ions of half the mass, since  $2m/2z = m/z$ .



Most organic molecules form molecular ions ( $M^+$ ) when the energy of the electron beam reaches 10–15 eV ( $\approx 10^3 \text{ kJ mol}^{-1}$ ). While this minimum *ionization potential* is of great theoretical importance, fragmentation of the molecular ion only reaches substantial proportions at higher bombardment energies, and 70 eV ( $\approx 6 \times 10^3 \text{ kJ mol}^{-1}$ ) is used for most organic work.

When the molecular ions have been generated in the ionization chamber, they are expelled electrostatically by means of a low positive potential on a repeller plate (A) in the chamber. Once out, they are accelerated down the ion tube by the much higher potential between the accelerating plates B and C (several thousand volts). Initial focusing of the ion beam is effected by a series of slits.

**Theory.** In a magnetic analyzer ions are separated on the basis of  $m/z$  values, and a number of equations can be brought to bear on the behavior of ions in the magnetic field.

The kinetic energy,  $E$ , of an ion of mass  $m$  travelling with velocity  $v$  is given by the familiar  $E = \frac{1}{2}mv^2$ . The potential energy of an ion of charge  $z$  being repelled by an electrostatic field of voltage  $V$  is  $zV$ . When the ion is repelled, the potential energy,  $zV$ , is converted into the kinetic energy,  $\frac{1}{2}mv^2$ , so that

$$zV = \frac{1}{2}mv^2$$



The mass spectrum of a compound can be obtained on a smaller sample size (*in extremis* down to  $10^{-12}$  g) than for any other of the main spectroscopic techniques, the principal disadvantages being the destructive nature of the process, which precludes recovery of the sample, the difficulty of introducing small enough samples into the high-vacuum system needed to handle the ionic species involved and the high cost of the instruments. Mass spectrometry is unlike the other spectroscopic techniques met in this book in that it does not measure the interaction of molecules with the spectrum of energies found in the electromagnetic spectrum, but the output from the instrument has all other spectroscopic characteristics, in showing an array of signals corresponding to a spectrum of energies; to highlight this distinction, the name *mass spectrometry* is preferred.

### Different mass fragmentation patterns and structure elucidation

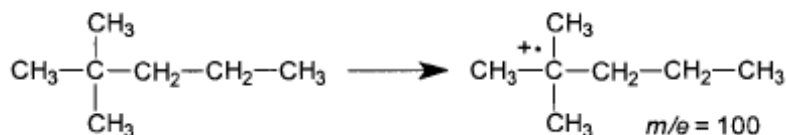
Three factors dominate the fragmentation processes:

- (a) **Weak bonds** tend to be broken most easily
- (b) **Stable fragments** (not only ions, but also the accompanying radicals and molecules) tend to be formed most readily
- (c) Some fragmentation processes depend on the ability of molecules to assume cyclic transition states.

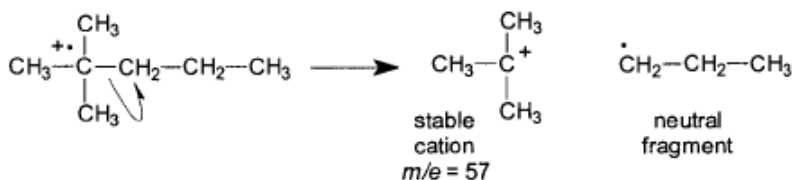
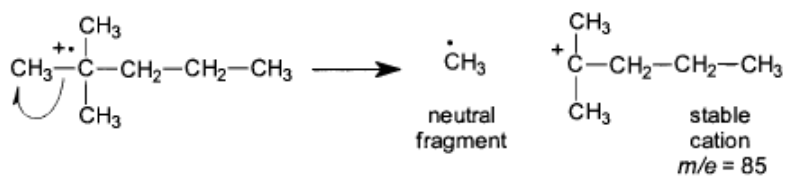
Favourable fragmentation processes naturally occur more often and ions thus formed give rise to strong peaks in the mass spectrum.

There are a number of common types of cleavage which are characteristic of various classes of organic compounds. These result in the loss of well-defined fragments which are characteristic of certain functional groups or structural elements.

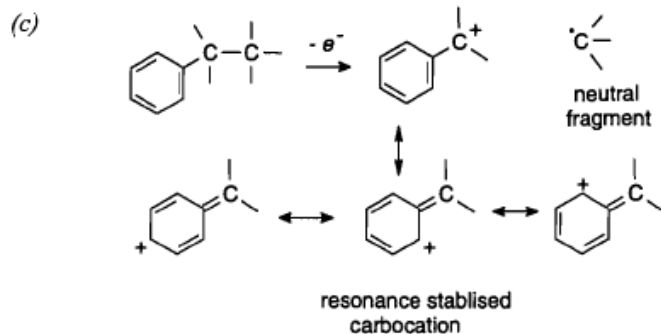
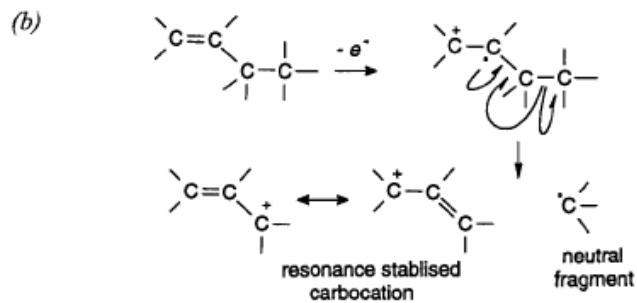
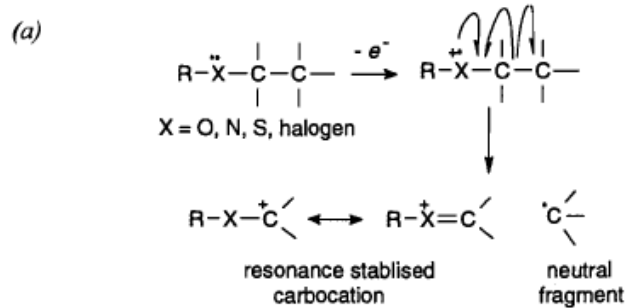
(1) **Cleavage at Branch Points.** Cleavage of aliphatic carbon skeletons at branch points is favoured as it leads to more substituted (and hence more stable) carbocations. The mass spectrum of 2,2-dimethylpentane shows strong peaks at  $m/e = 85$  and  $m/e = 57$  where cleavage leads to the formation of stable tertiary carbocations.



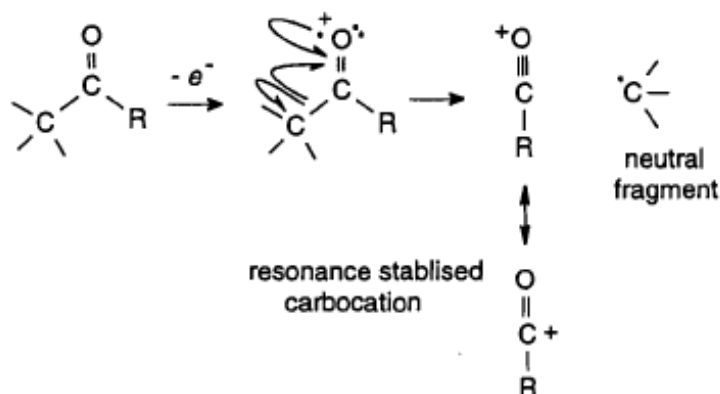




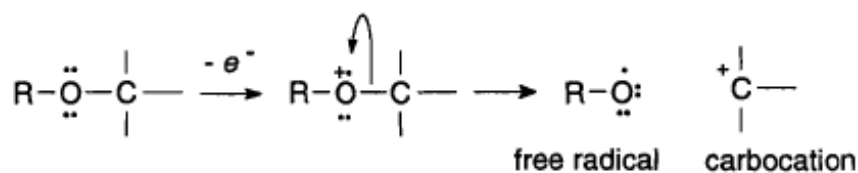
- (2) ***β* - Cleavage.** Chain cleavage tends to occur β to heteroatoms, double bonds and aromatic rings because relatively stable, delocalised carbocations result in each case.



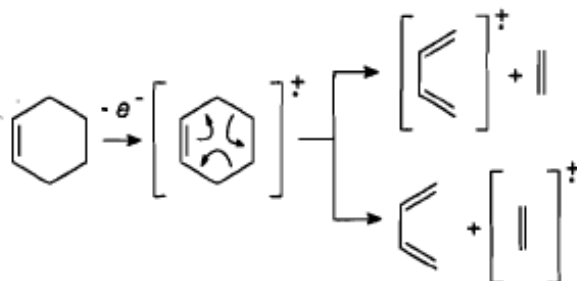
(3) **Cleavage  $\alpha$  to carbonyl groups.** Cleavage tends to occur  $\alpha$  to carbonyl groups to give stable acylium cations. R may be an alkyl, -OH or -OR group.



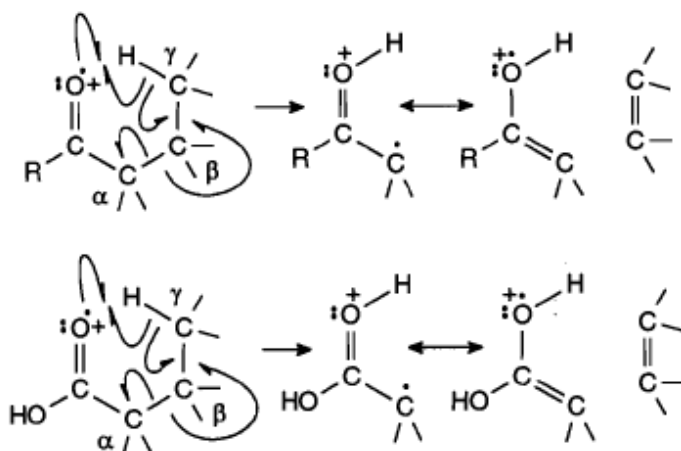
(4) **Cleavage  $\alpha$  to heteroatoms.** Cleavage of chains may also occur  $\alpha$  to heteroatoms, *e.g.* in the case of ethers:



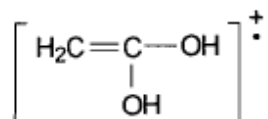
(5) **retro Diels-Alder reaction.** Cyclohexene derivatives may undergo a retro Diels-Alder reaction:



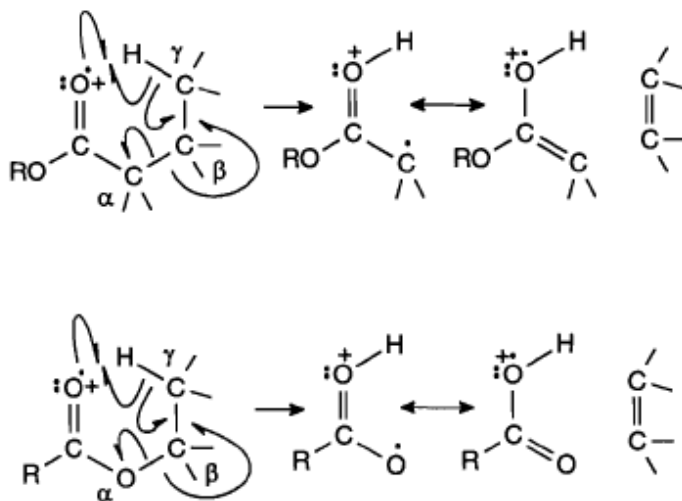
(6) **The McLafferty rearrangement.** Compounds where the molecular ion can assume the appropriate 6-membered cyclic transition state usually undergo a cyclic fragmentation, known as the **McLafferty rearrangement**. This rearrangement involves a transfer of a  $\gamma$  hydrogen atom to an oxygen and is often observed with ketones, acids and esters:



With primary carboxylic acids, R-CH<sub>2</sub>-COOH, this fragmentation leads to a characteristic peak at  $m/e = 60$



With carboxylic esters, two types of McLafferty rearrangements may be observed and ions resulting from either fragmentation pathway are observed in the mass spectrum:



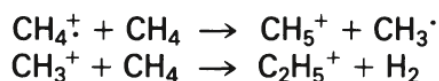
## 5S.1 ALTERNATIVES TO ELECTRON-IMPACT IONIZATION

The ability to measure accurately the relative molecular mass (molecular weight) of organic compounds by mass spectrometry is only possible if a sufficiently stable molecular ion can be formed, and we have seen that many classes of compound do not do so when electron-impact ionization is used. Partly, the reason lies in the large amount of excess energy imparted to the molecular ion by 70 eV bombardment; not only does this lead to rapid decomposition of many molecular ions, but also very complex fragmentation patterns often result. Some useful alternative methods of ionization are worth noting, each of which goes some way toward complementing the data obtained from conventional 70 eV spectra.

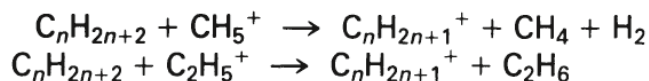
### 5S.1.1 Chemical ionization

This is brought about by mixing the sample at  $1.3 \times 10^{-2} \text{ N m}^{-2} \equiv 10^{-4} \text{ Torr}$  with a reactant gas (at  $1.3 \times 10^2 \text{ N m}^{-2} \equiv 1 \text{ Torr}$ )

and submitting this mixture to electron bombardment. The reactant gas most commonly used is methane, although other gases such as ammonia or isobutane have also been used: on electron impact, it is the methane which is ionized, and two ensuing ion-molecule reactions are important:



The  $\text{CH}_5^+$  and  $\text{C}_2\text{H}_5^+$  ions then react with sample molecules, inducing them to ionize, and these ions are separated magnetically and electrostatically in the normal way. Unfortunately,  $\text{CH}_5^+$  and  $\text{C}_2\text{H}_5^+$  do not react with all classes of organic compound in the same way: for *n*-alkanes the base peak is normally the  $M - 1$  peak at  $\text{C}_n\text{H}_{2n+1}^+$ , whereas for many basic compounds (amines, alkaloids, amino acids) the base peak is the  $M + 1$  peak. The  $M + 1$  peaks arise by protonation of nitrogen, and for the alkanes the  $M - 1$  peaks can be explained by the following reactions:



The principal advantages of chemical ionization over electron impact are: (a) more abundant peaks related to the molecular ion, whether  $M^+$  or  $M + 1$  or  $M - 1$ ; (b) simpler fragmentation patterns, which make it easier in many cases to study the kinetics of reaction of individual ions; (c) easy application of gas chromatography-mass spectrometry interfacing, since methane can be used not only as reactant gas (in the chemical ionization), but also as the carrier gas in the gas chromatograph (see section 5S.2).

### 5S.1.2 Field ionization and field desorption

An organic compound in the gas phase can be ionized when the molecules pass near a sharp metal anode carrying an electric field of the order of  $10^{10} \text{ V m}^{-1}$ . Electrons are 'sucked' from the sample molecules into incomplete orbitals in the metal, and the resulting molecular ions are then repelled toward a slit cathode. Primary focusing takes place at the cathode slit before the ions pass through the entrance slit of the mass spectrometer to be focused magnetically and electrostatically, as in electron-impact studies.

As in the case of chemical ionization, the principal advantages of field ionization from an organic chemist's point of view are the increased abundance of molecular ions and the minimization of complex fragmentations and rearrangements. Disadvantages are the lower sensitivity and resolution obtained.

Outstanding advantages can be achieved by a modification of the technique in which the sample is deposited directly onto the anode, and the high field produces not only ionization, but also desorption. Unstable and involatile material can be handled in this way, and molecular ion peaks have thus been produced from complex naturally occurring compounds (notably the carbohydrates) that do not show  $M^+$  on electron impact.

This method is named *field desorption* (FD).

### 5S.1.3 Desorption by lasers, plasmas, ions and atoms—LD and LIMA, PD, SIMS and FAB

In the search for soft ionization techniques for measuring the relative molecular masses of large biomolecules, irradiation or bombardment of the sample by several species has been developed; these include lasers, nuclear fission fragments, ions and neutral atoms or molecules. Recordings of the molecular masses of the molecule of insulin ( $m/z$  5733), chlorophyll oligomers ( $m/z$  ca 6000) and a dodeca-nucleotide dimer ( $m/z$  12 637) have been successful examples. Studies have been made on molecules with  $M_r$  values in excess of 20 000 daltons.

In some of these techniques the sample is coated on to a metal surface before being bombarded, and the ions produced often include  $(M + H)^+$  and  $(M - M)^-$  in addition to  $M^+$ , this being dependent *inter alia* on the type of molecule (acidic, basic, etc.) being bombarded.

*Laser ionization mass analysis* (LIMA) involves irradiation of the sample with a pulsed laser, of output up to  $10^5 \text{ W cm}^{-2}$ , which vaporizes a minute amount of material from the surface of the sample: this vaporized plume contains ions and neutrals, which are

then passed to a mass spectrometer for analysis. Ionization of the vapor plume may be enhanced with a second high-power laser pulse, or by electron impact, etc. Using microscopy, the initial laser pulse can be focused on extremely small areas, one or two micrometers across, which makes LIMA a valuable analytical tool for surface analysis in the polymers and microelectronics industries for detection of impurities in printed-circuit boards, microchips, etc. The layer structure of devices can be investigated (*depth profiling*) by applying a succession of pulses to the same area, each pulse cutting away a few micrometers at a time, enabling mass analysis over an effective cross-section of the material. LIMA is widely used for elemental analysis, but organic materials are amenable to the method.



## <sup>1</sup>HNMR: Basic Concepts

As is implied in the name, nuclear magnetic resonance (or NMR) is concerned with the magnetic properties of certain atomic nuclei, notably the nucleus of the hydrogen atom—the proton—and that of the carbon-13 isotope of carbon.

Studying a molecule by NMR spectroscopy enables us to record differences in the magnetic properties of the various magnetic nuclei present, and to deduce in large measure what the positions of these nuclei are within the molecule. We can deduce how many different kinds of environments there are in the molecule, and also which atoms are present in neighboring groups. Usually we can also measure how many atoms are present in each of these environments.

The most appropriate starting point for a study of NMR is the proton: it is the simplest nucleus, and it was the nucleus on which the phenomenon of NMR was first observed. (Felix Bloch and Edward M. Purcell shared the Nobel Prize in physics for this, their early but independent studies being reported nearly simultaneously in 1946.) Carbon-13 NMR is of equal importance, and it will be treated extensively; other magnetic nuclei (such as fluorine-19, phosphorus-31, nitrogen-14, nitrogen-15 and oxygen-17) will be surveyed more selectively.

### **3.1 THE NMR PHENOMENON**

#### **3.1.1 THE SPINNING NUCLEUS**

The nucleus of the hydrogen atom (the proton) behaves as a tiny spinning bar magnet, and it does so because it possesses both electric charge and mechanical spin; any spinning charged body will generate a magnetic field, and the nucleus of hydrogen is no exception.

#### **3.1.2 THE EFFECT OF AN EXTERNAL MAGNETIC FIELD**

Like all bar magnets, the proton will respond to the influence of an external magnetic field, and will tend to align itself with that field, in the manner of a compass needle in the earth's magnetic field. Because of quantum restrictions which apply to nuclei but not to compass needles (see section 3.2), the proton can only adopt two orientations with respect to an external magnetic field—either *aligned with the field* (the lower energy state) or *opposed to the field* (the higher energy state). We can also describe these orientations as *parallel* with or *antiparallel* with the applied field.

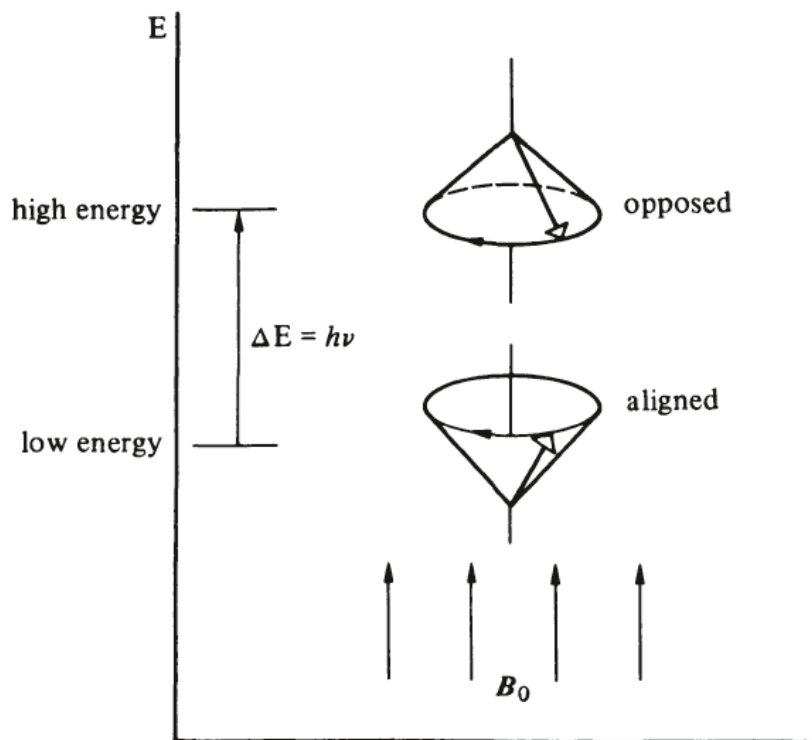
### 3.1.3 PRECESSIONAL MOTION

Because the proton is behaving as a *spinning* magnet, not only can it align itself with or oppose an external magnetic field, but also it will move in a characteristic way under the influence of the external magnet.

Consider the behavior of a spinning top: as well as describing its spinning motion, the top will (unless absolutely vertical) also perform a slower waltz-like motion, in which the spinning axis of the top moves slowly

around the vertical. This is *precessional* motion, and the top is said to be *precessing* around the vertical axis of the earth's gravitational field. The precession arises from the interaction of spin—that is, gyroscopic motion—with the earth's gravity acting vertically downward. Only a spinning top will precess; a static top will merely fall over.

As the proton is a spinning magnet, it will, like the top, precess around the axis of an applied external magnetic field, and can do so in two principal orientations, either aligned with the field (low energy) or opposed to the field (high energy). This is represented in figure 3.2, where  $B_0$  is the external magnetic field.



**Figure 3.2** Representation of precessing nuclei, and the  $\Delta E$  transition between the aligned and opposed conditions.



#### 3.1.4 PRECESSIONAL FREQUENCY

The spinning frequency of the nucleus does not change, but the speed of precession does. The *precessional frequency*,  $\nu$ , is directly proportional to the strength of the external field,  $B_0$ : that is,

$$\nu \propto B_0$$

This is one of the most important relationships in NMR spectroscopy, and it is restated more quantitatively in section 3.2.

As an example, a proton exposed to an external magnetic force of 1.4 T ( $\equiv 14\,000$  gauss) will precess  $\approx 60$  million times per second, so that  $\nu = 60$  MHz. For an external field of 2.3 T,  $\nu$  is  $\approx 100$  MHz, and at 14.1 T  $\nu$  is  $\approx 600$  MHz. (Strictly, the tesla is a measure of magnetic flux density, not field strength.)

#### 3.1.5 ENERGY TRANSITIONS

We have seen that a proton, in an external magnetic field of 1.4 T, will be precessing at a frequency of  $\approx 60$  MHz, and be capable of taking up one of two orientations with respect to the axis of the external field—aligned or opposed, parallel or antiparallel.

If a proton is precessing in the *aligned* orientation, it can absorb energy and pass into the *opposed* orientation; subsequently it can lose this extra energy and relax back into the aligned position. If we irradiate the precessing nuclei with a beam of radiofrequency energy of the correct frequency, the low-energy nuclei may absorb this energy and move to a higher energy state. The precessing proton will only absorb energy from the radiofrequency source if the precessing frequency is the same as the frequency of the radiofrequency beam; when this occurs, the nucleus and the radiofrequency beam are said to be *in resonance*; hence the term *nuclear magnetic resonance*.

The simplest NMR experiment consists in exposing the protons in an organic molecule to a powerful external magnetic field; the protons will precess, although they may not all precess at the same frequency. We irradiate these precessing protons with radiofrequency energy of the appropriate frequencies, and promote protons from the low-energy (aligned) state to the high-energy (opposed) state. We record this absorption of energy in the form of an NMR spectrum, such as that for toluene in figure 3.1(a).

### 3.2 THEORY OF NUCLEAR MAGNETIC RESONANCE

The only nuclei that exhibit the NMR phenomenon are those for which the spin quantum number  $I$  is greater than 0: the spin quantum number  $I$  is associated with the mass number and atomic number of the nuclei as follows:

<i>Mass number</i>	<i>Atomic number</i>	<i>Spin quantum number</i>
odd	odd or even	$\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots$
even	even	0
even	odd	1, 2, 3, . . .

The nucleus of  $^1\text{H}$ , the proton, has  $I = \frac{1}{2}$ , whereas  $^{12}\text{C}$  and  $^{16}\text{O}$  have  $I = 0$  and are therefore nonmagnetic. If  $^{12}\text{C}$  and  $^{16}\text{O}$  had been magnetic, the NMR spectra of organic molecules would have been much more complex.

In an applied magnetic field, magnetic nuclei like the proton precess at a frequency  $\nu$ , which is proportional to the strength of the applied field. The exact frequency is given by

$$\nu = \frac{\gamma B_0}{2\pi}$$

where  $B_0$  = strength of the applied external field experienced by the proton,

$\gamma$  = magnetogyric ratio, being the ratio between the nuclear magnetic moment,  $\mu$ , and the nuclear angular momentum,  $I$ :  
 $\gamma$  is also called the gyromagnetic ratio.

Typical approximate values for  $\nu$  are shown in table 3.1 for selected values of field strength  $B_0$ , for common magnetic nuclei.

The strength of the signal, and, hence, the sensitivity of the NMR experiment for a particular nucleus, are related to the magnitude of the magnetic moment,  $\mu$ . The magnetic moments of  $^1\text{H}$  and  $^{19}\text{F}$  are relatively large, and detection of NMR with these nuclei is fairly sensitive. The magnetic moment for  $^{13}\text{C}$  is about one-quarter that of  $^1\text{H}$ , and that of  $^2\text{H}$  is roughly one-third the moment of  $^1\text{H}$ ; these nuclei are less sensitively detected in NMR. (In contrast, the magnetic moment of the free electron is nearly 700 times that of  $^1\text{H}$ , and resonance phenomena for free radicals can be studied in extremely dilute solutions; see section 3S.7 for a discussion on electron spin resonance.)

What happens when protons absorb 60 MHz radiofrequency energy?

Nuclei in the lower energy state undergo transitions to the higher energy state; the populations of the two states may approach equality, and if this arises, no further net absorption of energy can occur and the observed resonance signal will fade out. We describe this situation in practice as *saturation* of the signal. In the recording of a normal NMR spectrum, however, the populations in the two spin states do not become equal, because higher-energy nuclei are constantly returning to the lower-energy spin state.

How can the nuclei lose energy and undergo transitions from the high- to the low-energy state?

The energy difference,  $\Delta E$ , can be reemitted as 60 MHz energy, and this can be monitored by a radiofrequency detector as evidence of the resonance condition having been reached. Of great importance, however, are two *radiationless* processes, which enable high-energy nuclei to lose energy.

The high-energy nucleus can undergo energy loss (or *relaxation*) by transferring  $\Delta E$  to some electromagnetic vector present in the surrounding environment. For example, a nearby solvent molecule, undergoing continuous vibrational and rotational changes, will have associated electrical and magnetic changes, which might be properly oriented and of the correct dimension to absorb  $\Delta E$ . Since the nucleus may be surrounded by a whole array of neighboring atoms, either in the same molecule or in solvent molecules, etc., this relaxation process is termed *spin-lattice relaxation*, where *lattice* implies the entire framework or aggregate of neighbors.

A second relaxation process involves transferring  $\Delta E$  to a neighboring nucleus, provided that the particular value of  $\Delta E$  is common to both nuclei: this mutual exchange of spin energy is termed *spin-spin relaxation*. While one nucleus loses energy, the other nucleus gains energy, so that no net change in the populations of the two spin states is involved.

The rates of relaxation by these processes are important, and in particular the rate of spin-lattice relaxation determines the rate at which *net* absorption of 60 MHz energy can occur.

Rather than define the *rate constants* ( $k$ ) for these first-order relaxation mechanisms, a *spin-lattice relaxation time* ( $T_1$ ) is defined, being the reciprocal of  $k$ .  $T_1$  is related to the half-life of the exponential process by  $T_1 = (\text{half-life})/\ln 2$ .  $T_2$  is similarly defined as the *spin-spin relaxation time*. A more rigorous treatment of relaxation is given in section 3S.3. If  $T_1$  and  $T_2$  are small, then the lifetime of an excited nucleus is short, and it has been found that this gives rise to very broad absorption lines in the NMR spectrum. If  $T_1$  and  $T_2$  are large, perhaps of the order of 1s, then sharp spectral lines arise.

For nonviscous liquids (and that includes solutions of solids in nonviscous solvents) molecular orientations are random, and transfer of energy by spin-lattice relaxation is inefficient. In consequence,  $T_1$  is large, and this is one reason why sharp signals are obtained in NMR studies on nonviscous systems.

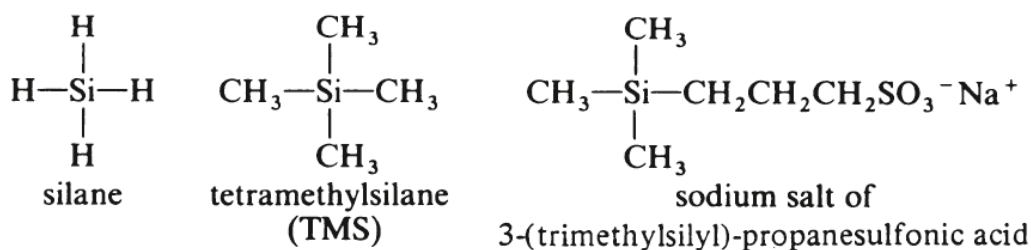
The important relationship between relaxation times and line broadening can be understood qualitatively by using the uncertainty principle in the form  $\Delta E \cdot \Delta t \approx h/2\pi$ , or, since  $E = h\nu$ ,  $\Delta\nu \cdot \Delta t \approx 1/2\pi$ . Expressed verbally, the product  $\Delta\nu \cdot \Delta t$  is constant, and if  $\Delta t$  is large (that is, the lifetime of a particular energy state is long), then  $\Delta\nu$  must be small (that is, the uncertainty in the measured frequency must be small, so that there is very little 'spread' in the frequency, and line-widths are narrow). Conversely, if  $\Delta t$  is small (fast relaxation), then  $\Delta\nu$  must be large, and broad lines appear.



## Chemical shift, factors affecting chemical shift, spin relaxation, spin-spin coupling

### 3.3.1 MEASUREMENT OF CHEMICAL SHIFT—INTERNAL STANDARDS

To measure the precessional frequency of a group of nuclei in absolute frequency units is not difficult but is rarely required. More commonly the *differences* in frequency are measured with respect to some reference group of nuclei. For protons and  $^{13}\text{C}$ , the universally accepted reference is tetramethylsilane, TMS:



TMS is chosen because it gives an intense sharp signal even at low concentrations (having 12 protons in magnetically equivalent positions); the signal arises on the NMR spectrum well clear of most common organic protons (for reasons we shall meet in section 3.4); it is chemically inert and has a low boiling point, so that it is easily removed from a recoverable sample of a valuable organic compound; it is soluble in most organic solvents, and can be added to the sample solution (0.01–1.0 per cent) as an *internal standard*.

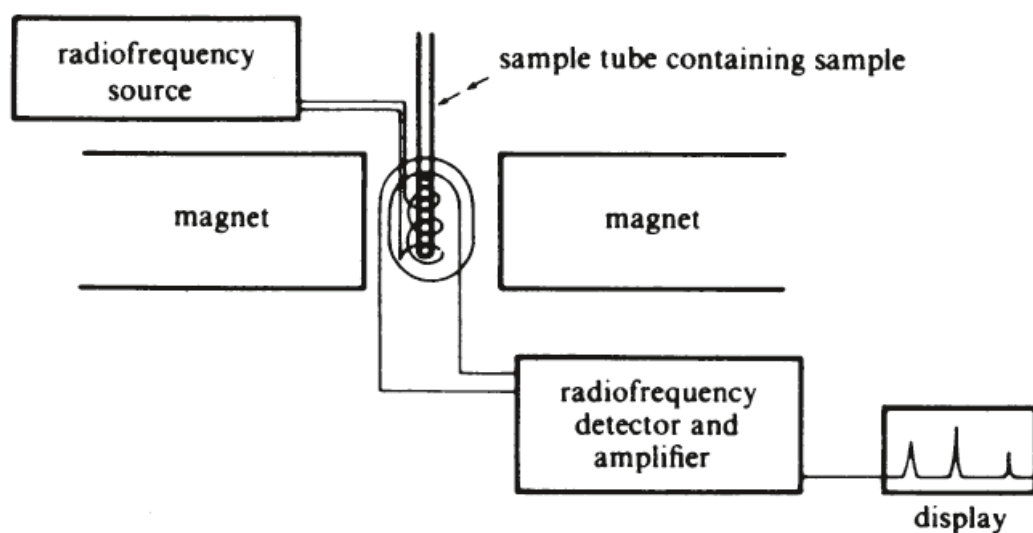
TMS is not soluble in water or in  $\text{D}_2\text{O}$ ; for solutions in these solvents the sodium salt of 3-(trimethylsilyl)-propanesulfonic acid is used.

The choice of standards against which to measure the precessional frequency of other nuclei is based on the same criteria. TMS is used for  $^{13}\text{C}$ ;  $\text{CFCl}_3$  for  $^{19}\text{F}$ ; an *external* sample of concentrated  $\text{H}_3\text{PO}_4$  for  $^{31}\text{P}$ ; and although liquid ammonia (external) is the absolute frequency standard for  $^{15}\text{N}$ , nitromethane ( $\text{CH}_3\text{NO}_2$ ) is commonly used as a more convenient primary standard. Water is the standard for  $^{17}\text{O}$ .

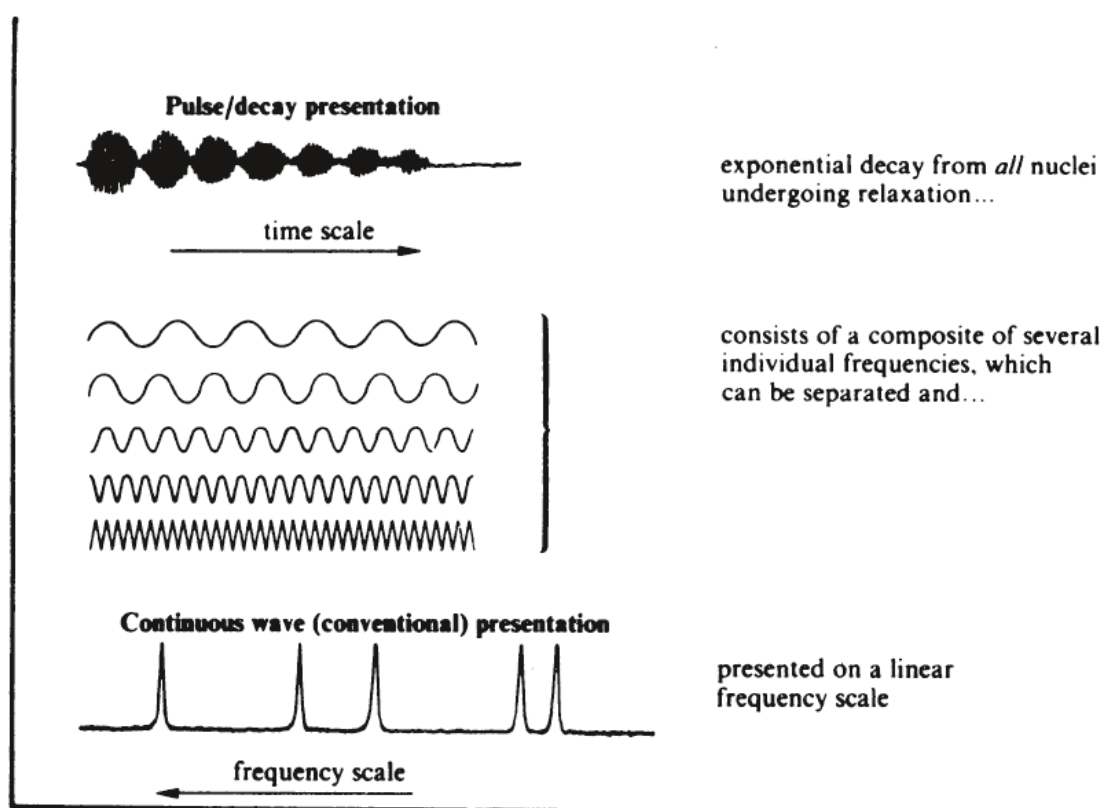
### 3.3.2 MEASUREMENT OF CHEMICAL SHIFT—THE NMR SPECTROMETER

The basic features of the instrumentation needed to record an NMR spectrum are a magnet, a radiofrequency source and a detection system to indicate that energy is being transferred from the radiofrequency beam to the nucleus. Such an arrangement is shown schematically in figure 3.3.

Magnet strengths and frequencies depend on the various factors discussed above, but typical practical parameters for proton NMR will be used for this discussion.



(a)



(b)

**Figure 3.3** (a) Basic features of an NMR spectrometer. (b) Schematic representation of pulsed NMR; the output in the time domain (the free induction decay, FID) is converted to the frequency domain

### 3.4 FACTORS INFLUENCING CHEMICAL SHIFT

#### 3.4.1 ELECTRONEGATIVITY—SHIELDING AND DESHIELDING

Table 3.2 shows the chemical shift positions for CH<sub>3</sub> protons when a methyl group is attached to functions of increasing electronegativity. As the electronegativity of the function is increased, the CH<sub>3</sub> protons come to resonance at higher  $\delta$  values.

**Table 3.2** Chemical shift values for CH<sub>3</sub> protons attached to groups of varying electronegativity

<i>Compound</i>	<i>Chemical shift/<math>\delta</math></i>
$\text{CH}_3 - \text{Si} -$   	0.0
CH <sub>3</sub> I	2.16
CH <sub>3</sub> Br	2.65
CH <sub>3</sub> Cl	3.10
CH <sub>3</sub> F	4.26

Hydrogen nuclei are surrounded by electron density, which to some extent *shields* the nucleus from the influence of the applied field  $B_0$ , and the extent of this shielding will influence the precessional frequency of the nucleus—the greater the *shielding effect*, the lower the precessional frequency. In a magnetic field the electrons around the proton are induced to circulate, and in so doing they generate a small secondary magnetic field, which acts in opposition (that is, diamagnetically) to the applied field (see figure 3.5(a)). The greater the electron density circulating around the proton, the greater the induced diamagnetic shielding effect and the lower the precessional frequency of the proton. Electronegative groups, such as fluorine in CH<sub>3</sub>F, withdraw electron density from the methyl group (inductive effect) and this *deshielding effect* means that the methyl protons experience a greater net magnetic field, and, hence, precess with higher frequency. Since fluorine is more electronegative than chlorine, its deshielding influence is greater and, hence, the attached protons have higher precessional frequencies (higher  $\delta$  values).

Silicon is electropositive, and the opposite effect operates in, for example, TMS; silicon pushes electrons into the methyl groups of TMS by a +I inductive effect, and this powerful *shielding effect* means that the TMS protons come to resonance at low frequency (low  $\delta$  value, defined as zero).

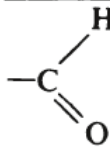
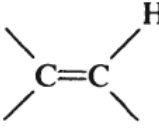
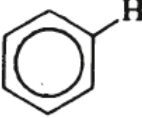

The effect of charged species on chemical shift values is very marked; protons adjacent to N<sup>+</sup> (as in quaternary ammonium ions, R<sub>4</sub>N<sup>+</sup>) are very strongly deshielded (high  $\delta$  values), while carbanionic centers act as powerful shielding influences (low  $\delta$  values).

#### 3.4.2 VAN DER WAALS DESHIELDING

In a rigid molecule it is possible for a proton to occupy a sterically hindered position, and in consequence the electron cloud of the hindering group will tend to repel, by electrostatic repulsion, the electron cloud surrounding the proton. The proton will be deshielded and appear at higher  $\delta$  values than would be predicted in the absence of the effect. Although this influence is small (usually less than 1 ppm), it must be borne in mind when predicting the chemical shift positions in overcrowded molecules such as highly substituted steroids or alkaloids.

#### 3.4.3 ANISOTROPIC EFFECTS

The chemical shift positions ( $\delta$ ) for protons attached to  $C=C$  in alkenes is higher than can be accounted for by electronegativity effects alone. The same is true of aldehydic protons and aromatic protons, whereas alkyne protons appear at relatively low  $\delta$ . Table 3.3 lists approximate  $\delta$  values for these protons.

Structure	Approximate chemical shift range/ $\delta$
	9.5–10.0
	4–8
	6–9
	1.5–3.5

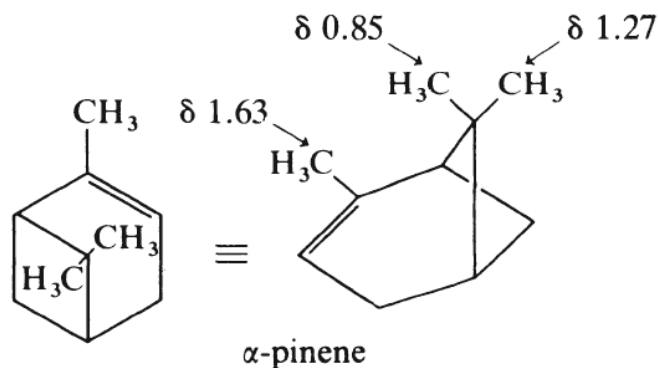
The explanation is again collated with the manner in which electrons, in this case  $\pi$  electrons, circulate under the influence of the applied field. The effect is complex, and can lead to shifts to higher frequency (downfield shifts, or paramagnetic shifts) or to lower frequency (upfield shifts, or diamagnetic shifts). In addition, the effects are paramagnetic in certain directions around the  $\pi$  clouds, and diamagnetic in others, so that these effects are described as *anisotropic*, as opposed to *isotropic* (operating equally through space).



*Alkenes.* When an alkene group is so oriented that the plane of the double bond is at  $90^\circ$  to the direction of the applied field (as in figure 3.5(b)), induced circulation of the  $\pi$  electrons generates a secondary magnetic field, which is diamagnetic around the carbon atoms, but paramagnetic (that is, it augments  $B_0$ ) in the region of the alkene protons.

Where the direction of the induced magnetic field is parallel to the applied field,  $B_0$ , the net field is greater than  $B_0$ . Protons in these zones come to resonance therefore at higher  $\delta$  values than expected.

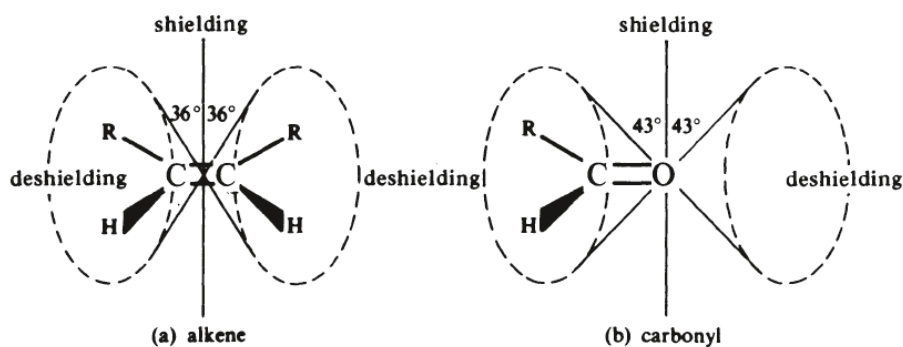
Any group held above or below the plane of the double bond will experience a *shielding effect*, since in these areas the induced field opposes  $B_0$ . In  $\alpha$ -pinene one of the geminal methyl groups is held in just such a shielded position, and comes to resonance at significantly lower  $\delta$  (frequency) than its twin. The third methyl group appears at higher  $\delta$  (frequency), since it lies *in* the plane of the double bond and is thus *deshielded*.



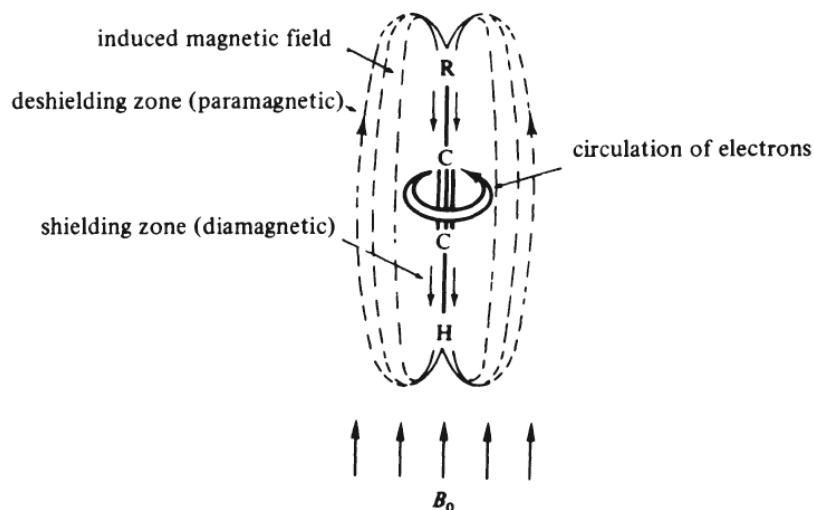
In summary, we can divide the space around a double bond into two categories, as shown in figure 3.6(a). Deshielding occurs in the cone-shaped zones, and in these zones  $\delta$  values will tend to be higher. Shielding is found outside the cones and protons in these zones are shielded (lower  $\delta$  values).

*Carbonyl compounds.* For the carbonyl group a similar situation arises, although the best representation of shielding and deshielding zones is slightly different from the alkene pattern; see figure 3.6(b) Two cone-shaped volumes, centered on the oxygen atom, lie parallel to the axis of the

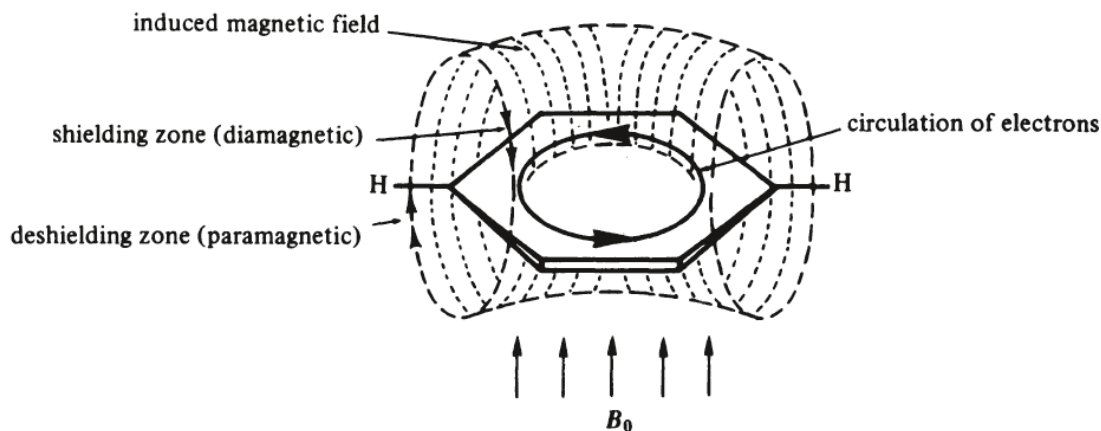
$\text{C}=\text{O}$  bond; protons within these cones experience deshielding, so that aldehydic protons, and the formyl protons of formate esters, appear at high  $\delta$  values. Protons held above or below these cones will come to resonance at lower  $\delta$  values.



**Alkynes.** Whereas alkene and aldehydic protons appear at high  $\delta$  values, alkyne protons appear around  $\delta$  1.5–3.5. Electron circulation around the triple bond occurs in such a way that the protons experience a *diamagnetic shielding* effect. Figure 3.7 shows how this arises, when the axis of the alkyne group lies parallel to the direction of  $B_0$ . The cylindrical sheath of  $\pi$  electrons is induced to circulate around the axis, and the resultant annulus-shaped magnetic field acts in a direction that opposes  $B_0$  in the vicinity of the protons. These protons experience lower values of field; therefore, acetylenic protons appear at low  $\delta$  values in the spectrum.



**Aromatic compounds.** In the molecule of benzene (and aromatic compounds in general)  $\pi$  electrons are delocalized cyclically over the aromatic ring. These loops of electrons are induced to circulate in the presence of the applied field,  $B_0$ , producing a substantial electric current, called the *ring current*. The magnetic field associated with this electric field has the geometry and direction shown in figure 3.8. (An analogy in the macro-world is a ring of copper wire moved into a magnetic field: electric current flows in the wire, and sets up a magnetic field similar in geometry and direction to that shown for benzene in figure 3.8.)

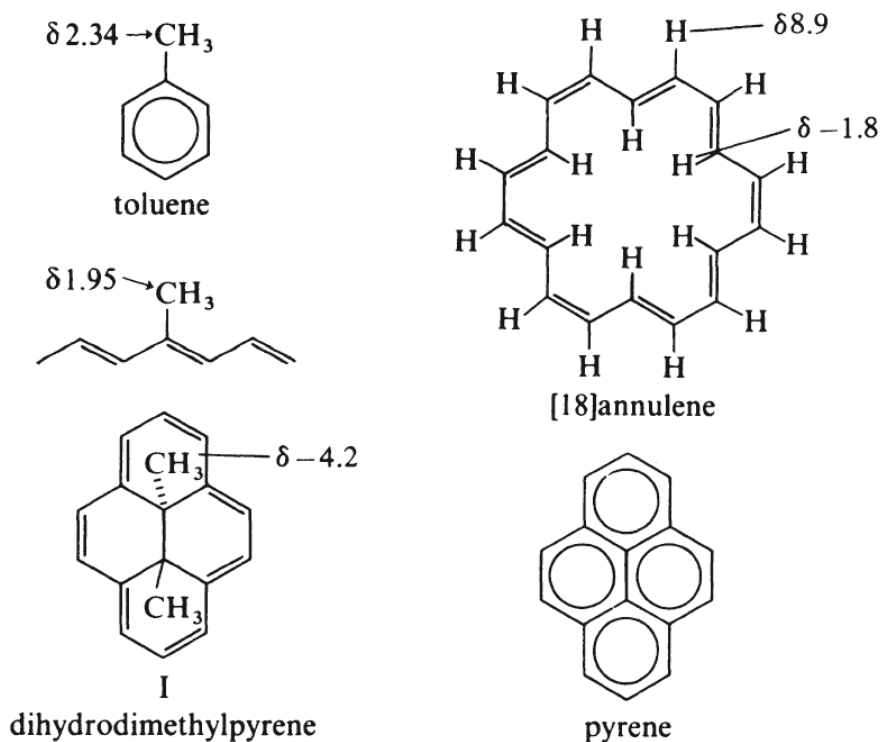


The induced field is diamagnetic (opposing  $B_0$ ) in the center of the ring, but the returning flux outside the ring is paramagnetic (augmenting  $B_0$ ).

Protons around the periphery of the ring experience an augmented magnetic field, and consequently come to resonance at higher  $\delta$  values than would otherwise be so. Protons held above or below the plane of the ring resonate at low  $\delta$  values. Two examples will illustrate the magnitude of these effects.

In the molecule of toluene the methyl protons resonate at  $\delta$  2.34, whereas a methyl group attached to an acyclic conjugated alkene appears at  $\delta$  1.95. This is some measure of the greater deshielding influence of the ring current in aromatic compounds (cyclically delocalized  $\pi$  electrons) compared with the deshielding of conjugated alkene groups (having no cyclic delocalization). Indeed, so important is this observation that NMR has become one of the principal criteria used in deciding whether an organic compound has substantial aromatic character (at least in so far as aromatic character relates to cyclic delocalization of  $(4n + 2)$   $\pi$  electrons).

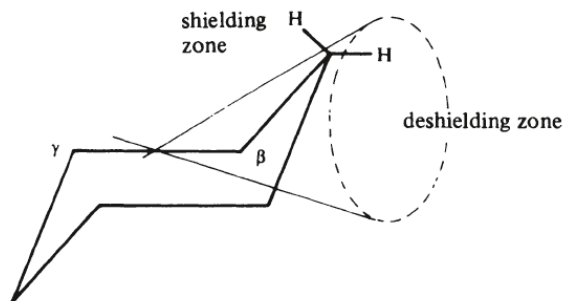
One of the most dramatic observations in NMR work on aromatic systems involves the dimethyl derivative of pyrene (I), in which the methyl groups appear at  $\delta$  -4.2, *lower* in frequency than TMS. This shows that the cyclic  $\pi$  electron system around the periphery of the molecule sustains a substantial ring current, and therefore indicates aromatic character in a nonbenzenoid ring system. The methyl groups are deep in the shielding zone of this ring current, and it is for this reason that they appear at such an extraordinary  $\delta$  value.



*Alkanes.* The equatorial protons in cyclohexane rings come to resonance about 0.5 ppm higher than axial protons, and this is attributed to anisotropic deshielding by the  $\sigma$  electrons in the  $\beta\gamma$  bonds, as shown in figure 3.9. The effect is small compared with the anisotropic influence of circulating  $\pi$  electrons, but is readily observed in rigid systems and also in mobile systems at low temperature.

Simple electronegative (inductive) effects operate only along a chain of atoms, the effect weakening with distance, but magnetic anisotropy operates through space irrespective of whether the influenced group is directly joined to the anisotropic group. For this reason the stereochemis-

try of molecules must be carefully studied to predict whether magnetically anisotropic groups are likely to have an influence on the chemical shift of apparently distant protons.



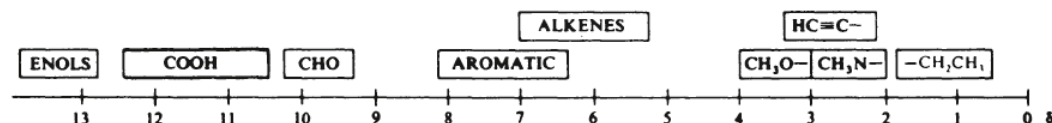
**Figure 3.9** Anisotropic shielding and deshielding in cyclohexanes.



### 3.5.1 USE OF CORRELATION TABLES

Although chemical shift data have been rationalized to a large extent, using the factors discussed above, much of the application of NMR to organic chemistry is what one might call 'explained empiricism'.

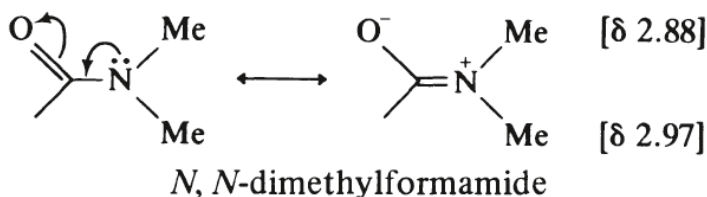
Predicting the  $^1\text{H}$  NMR spectrum of an organic compound begins with predicting the chemical shift positions for the different hydrogens in the molecule. Figure 3.10 is a useful chart containing approximate proton classifications, and all chemists working with NMR are thoroughly familiar with these allocations.



**Figure 3.10** Approximate chemical shift positions for protons in organic molecules.

### 3.5.2 INFLUENCE OF RESTRICTED ROTATION

The NMR spectrum of *N,N*-dimethylformamide,  $\text{HCONMe}_2$ , recorded around room temperature, shows *two* signals for the methyl groups, although it might have been expected that the two methyl groups would be in magnetically equivalent environments. Dimethylformamide is represented by the two resonance forms shown below, and the result of conjugation between the carbonyl group and the nitrogen nonbonding pair is to increase the double-bond character of the  $\text{C}-\text{N}$  bond sufficiently to restrict the rotation at room temperature: one methyl group is *cis* to



oxygen, the other is *trans*, and anisotropy of the carbonyl group is sufficient to influence the chemical shift position for the *cis* group. Using a heated probe in the NMR instrument (see section 3S.2), the spectrum of *N,N*-dimethylformamide can be recorded at high temperature ( $\approx 130^\circ\text{C}$ ), and this spectrum shows only one signal for the methyl groups; at elevated temperatures rotation around the  $\text{C}-\text{N}$  bond is so rapid that each methyl group experiences the same *time-averaged* environment.

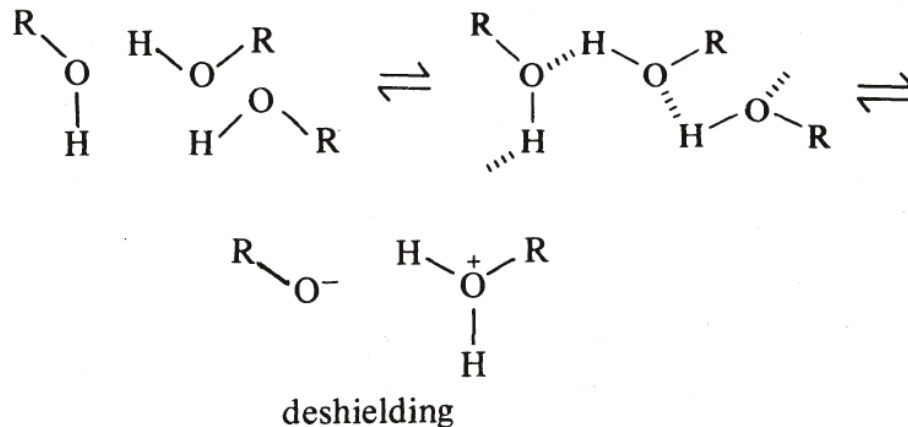
### 3.6.2 SOLVENT SHIFTS—CONCENTRATION AND TEMPERATURE EFFECTS—HYDROGEN BONDING

The solvents listed above vary considerably in their polarity and magnetic susceptibility. Not surprisingly, the NMR spectrum of a compound dissolved in one solvent may be slightly different from that measured in a

more polar solvent, and it is important in all NMR work to quote the solvent used. The NMR signals for protons attached to carbon are, in general, shifted only slightly by changing solvent, except where significant bonding or dipole-dipole interaction might arise: the NMR spectrum for chloroform dissolved in cyclohexane appears at  $\delta$  7.3, but in benzene solution the signal is moved by the exceptionally large amount of  $-1.56$  ppm (to  $\delta$  5.74). Benzene is behaving as a Lewis base to chloroform, and considerable charge transfer is responsible for altering the electron density around the chloroform proton, with concomitant shift in the signal to a lower  $\delta$  value. The benzene ring-current also contributes to this shift.

In contrast, NH, SH and, particularly, OH protons all have their NMR signals substantially moved on changing to solvents of differing polarity. This effect is largely associated with hydrogen bonding, and it is noted even when different concentrations are used in the same solvent.

At low concentrations intermolecular hydrogen bonding is diminished in simple OH, NH and SH compounds: since hydrogen bonding involves electron-cloud transfer from the hydrogen atoms to a neighboring electronegative atom (O, N or S), the hydrogen experiences a net deshielding effect when hydrogen bonding is strong, and is less deshielded when hydrogen bonding is diminished. Thus, at high concentrations (strong



Intermolecular H bonding raises  $\delta$  values:  $\delta$  values are lowered with increased dilution or temperature

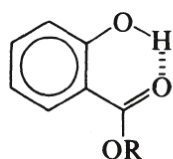
hydrogen bonding, strong deshielding) OH, NH and SH protons appear at higher  $\delta$  than in dilute solutions.

Table 3.8 lists the chemical shift positions for protons subject to hydrogen bonding, and it can be seen that the range within which they come to resonance is wide ( $\delta$  0.5–4.5 for simple alcohols).

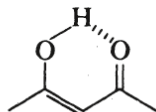
Increased temperature also reduces intermolecular hydrogen bonding, so the resonance positions for these protons are temperature-dependent (higher temperatures mean lower  $\delta$  values).

Intramolecular hydrogen bonding is unchanged by dilution and the NMR spectrum from such systems is virtually unaltered by varying concentration. Salicylates and enols of  $\beta$ -dicarbonyl compounds are examples of such systems: chelates, such as the salicylates, show the OH resonance at very high  $\delta$  (10–12), and enol OH appears even higher ( $\delta$  11–16).

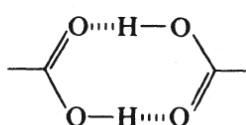
Carboxylic acids are a special case of hydrogen bonding because of their stable dimeric association, which persists even in very dilute solution; carboxylic OH appears between  $\delta$  10 and  $\delta$  13, usually nearer  $\delta$  11–12.



salicylates



enol of  $\beta$ -diketone



carboxylic acid dimer

Intramolecular H bonding:  $\delta$  values largely unaffected by concentration changes

### 3.8 SPIN-SPIN COUPLING—SPIN-SPIN SPLITTING

#### 3.8.1 THE SPLITTING OF NMR SIGNALS IN PROTON NMR SPECTRA

The  $^1\text{H}$  NMR spectrum of *trans*-cinnamic acid is reproduced in figure 3.11.

The aromatic protons, five in number, give rise to the peaks at  $\delta$  7.4 and  $\delta$  7.55, and the carboxyl proton is at  $\delta$  12.5; both of these signals we might have predicted from the discussions in sections 3.4 and 3.5.

What we would not have predicted from chemical shift data alone is that proton  $\text{H}_\text{A}$  appears as *two* lines on the spectrum (centered on  $\delta$  6.45), and proton  $\text{H}_\text{X}$  appears as *two* lines (centered on  $\delta$  7.8). We say that each signal is *split into a doublet*. Note that the separation between the two  $\text{H}_\text{A}$  lines is the same as the separation between the two  $\text{H}_\text{X}$  lines.

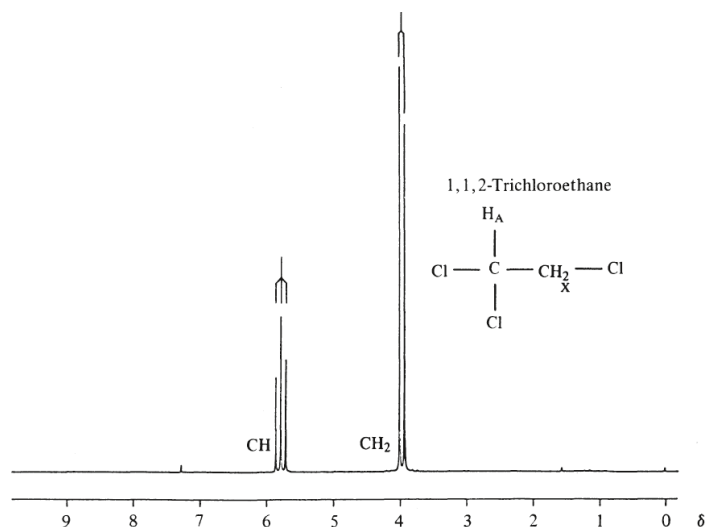
Look now at the spectrum of 1,1,2-trichloroethane (figure 3.12). The signal from proton  $\text{H}_\text{A}$  appears as a *triplet*, while that from protons  $\text{H}_\text{X}$  is a *doublet*.

*The number of lines (multiplicity) observed in the NMR signal for a group of protons is not related to the number of protons in that group; the multiplicity of lines is related to the number of protons in neighboring groups.*

For example, protons  $\text{H}_\text{X}$  in figure 3.12 have only *one* neighboring proton, and  $\text{H}_\text{X}$  appears as a two-line signal (doublet); proton  $\text{H}_\text{A}$  has *two* neighbors and the signal is split into three lines (triplet).

( $n + 1$ ) rule. *The simple rule is: to find the multiplicity of the signal from a group of protons, count the number of neighbors ( $n$ ) and add 1. (Exceptions to the rule are discussed in section 3.10).*



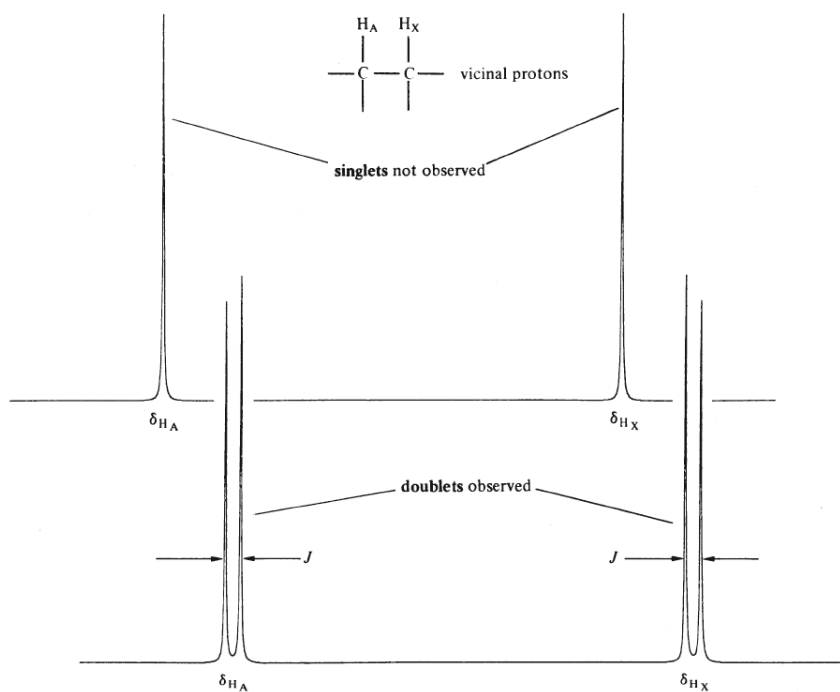


**Figure 3.12**  $^1\text{H}$  NMR spectrum of 1,1,2-trichloroethane. (80 MHz in  $\text{CDCl}_3$ .)

### 3.8.2 THEORY OF SPIN-SPIN SPLITTING

The diagram in figure 3.13 represents two vicinal protons similar to the alkene protons in cinnamic acid,  $\text{H}_A$  and  $\text{H}_X$ . These protons, having different magnetic environments, come to resonance at different positions in the NMR spectrum; they do not give rise to single peaks (singlets) but doublets. The separation between the lines of each doublet is equal: this spacing is called the *coupling constant*,  $J$ .

Why is the signal for proton A split into a doublet? A simplistic explanation is that the resonance position for A depends on its total magnetic environment; part of its magnetic environment is the nearby proton X, which is itself magnetic, and proton X can have its nuclear



magnet either *aligned with* proton A or *opposed to* proton A. Thus, proton A can either *increase* the net magnetic field experienced by A (X aligned) or *decrease* it (X opposed); in fact, it does both. The two spin orientations of X create two different magnetic fields around proton A: in roughly half of the molecules the spin orientation of X creates a shielding field around proton A, and in the other half a deshielding field. Therefore, proton A comes to resonance, not once, but twice, and proton A gives rise to a doublet.

Similarly, proton A is a magnet having two spin orientations with respect to X, and A creates two magnetic fields around X. Proton X comes to resonance twice in the NMR spectrum.

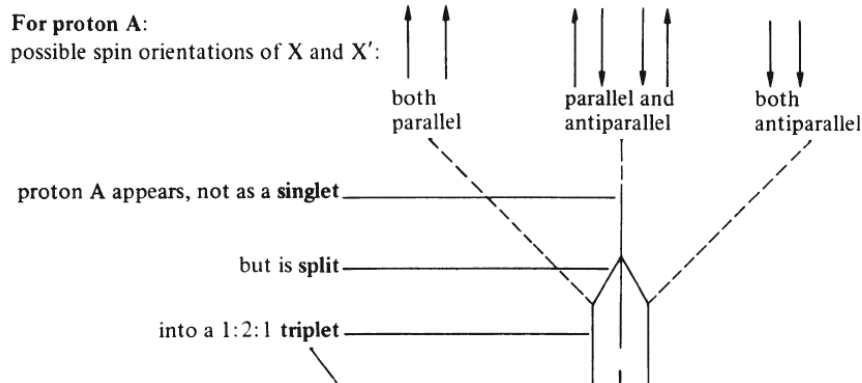
This mutual magnetic influence between protons A and X is not transmitted through space, but via the electrons in the intervening bonds. The nuclear spin of A couples with the electron spin of the C—H<sub>A</sub> bonding electrons; these, in turn, couple with the C—C bonding electrons and then with the C—H<sub>X</sub> bonding electrons. The coupling is eventually transmitted to the spin of the H<sub>X</sub> nucleus. This *electron-coupled* spin interaction operates strongly through one bond or two bonds, less strongly

through three bonds, and, except in unusual cases, rather weakly through four or more bonds. This point is more rigorously developed in the following section and in supplement 3S.1.

We can represent the possible spin orientations of coupling protons as in figure 3.14. Proton A can ‘see’ proton X as aligned (parallel ↑) or opposed antiparallel ↓); these two spin orientations correspond effectively to two different magnetic fields. Therefore, proton A comes to resonance twice. The same argument explains why proton X appears as a doublet.

The A and X protons of cinnamic acid give rise to this characteristic pair of doublets, caused by two protons undergoing spin coupling: such a spectrum is called an AX spectrum. Since the probability of the two spin orientations of A and X arising is equal in molecules throughout the sample, the two lines in each doublet are of equal intensity. (However, see section 3.10.)

Figure 3.15 represents the coupling that arises in the triplet signal in the NMR spectrum of 1,1,2-trichloroethane.



( $\downarrow \downarrow$ ); (3) one can be parallel and the other antiparallel, and this can arise in two ways—X parallel with X' antiparallel ( $\uparrow \downarrow$ ) or X antiparallel with X' parallel ( $\downarrow \uparrow$ ). Three distinct energy situations, (1), (2) and (3), are created, and therefore proton A gives rise to a triplet. The probability of the first two energy states arising is equal, but since the third state can arise in two different ways, it is twice as likely to arise; the intensity of the signal associated with this state is twice that of the lines associated with the first two states, and we see in the spectrum of 1,1,2-trichloroethane that the relative line intensities in the triplet are 1:2:1.

One can go further and predict the theoretical line intensities for quintets, sextets, etc., and find that the ratios are the same as the coefficients in the binomial expansion. Pascal's famous triangle serves to remind:

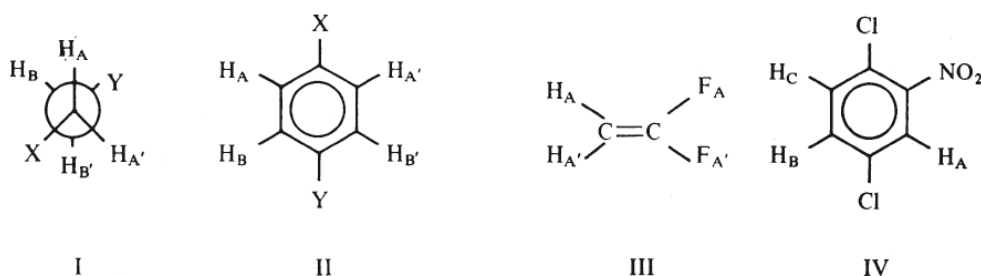
1	singlet
1 1	doublet
1 2 1	triplet
1 3 3 1	quartet
1 4 6 4 1	quintet
1 5 10 10 5 1	sextet

### 3.8.5 CHEMICAL AND MAGNETIC EQUIVALENCE IN NMR

We saw in section 3.5.2 that protons which are chemically indistinguishable, in terms of their synthetic reactivity, may nevertheless give rise to more complex NMR spectra than this might have implied. Having studied the separate phenomena of chemical shift and spin-spin coupling, we can now introduce a general set of criteria which govern these complications and therefore must be borne in mind in the analysis of many NMR spectra. The necessary definitions will be mainly presented with respect to proton NMR spectra, but the factors involved apply equally to the NMR spectra of any magnetic nuclei.

Consider that formula I below represents the most stable conformation of the molecule of  $\text{XCH}_2\text{—CH}_2\text{Y}$ : because of symmetry,  $\text{H}_\text{A}$  and  $\text{H}_\text{A}'$  will have the same chemical shift values, as will  $\text{H}_\text{B}$  and  $\text{H}_\text{B}'$ . Now  $\text{H}_\text{A}$  will undergo spin–spin coupling to  $\text{H}_\text{B}$ , but (assuming no rotation around the  $\text{C—C}$  bond) this will be different from the coupling of  $\text{H}_\text{A}'$  to  $\text{H}_\text{B}$ . We say that  $\text{H}_\text{A}$  and  $\text{H}_\text{A}'$  are *chemically equivalent* but are *magnetically non-equivalent*.

*Two protons are defined as being chemically equivalent if, by virtue of symmetry within the molecule, their electronic environments are indistinguishable and, therefore, they possess the same value of chemical shift.*



*Two protons are defined as being magnetically equivalent if each couples equally to a third neighboring proton; otherwise they are magnetically nonequivalent.*

The labels A, B, C, and so on, are allocated to each separate group of chemically equivalent nuclei; if two protons  $\text{H}_\text{A}$  are magnetically non-equivalent, this is indicated by the use of primes (thus,  $\text{H}_\text{A}$  and  $\text{H}_\text{A}'$ ). Similarly, protons,  $\text{H}_\text{B}$  and  $\text{H}_\text{B}'$ , must be chemically equivalent but magnetically nonequivalent.

Molecules II and III contain equivalent and nonequivalent groups of nuclei labelled to show the differences between chemical and magnetic equivalence. All *para*-substituted benzene derivatives of this type (II, where group X is different from group Y) show NMR spectra with recognizable features: see section 3.10. The two fluorine atoms in III are subject to the same considerations, and are chemically equivalent but magnetically nonequivalent.

*chemical equivalence* means simply *chemical shift equivalence*, and *magnetic equivalence* means *coupling equivalence*.

### Coupling Constant (J)

The number of bonds intervening between the coupling nuclei is important, since the coupling is transmitted via the electrons of these bonds. It is a convenient notation to indicate this number as a superscript to the symbol for the coupling constant. Thus, direct coupling (as in the



coupling of a proton with an attached carbon-13 nucleus,  $^1\text{C}-^1\text{H}$ ) would be a one-bond coupling,  $^1J$ ; the coupling between protons on a  $\text{CH}_2$  group would be symbolized by  $^2J$ ; that between protons on adjacent carbons as  $^3J$ ; and so on.

*Geminal coupling*, involving protons on  $-\text{CH}_2-$  groups, is strong,  $^2J$  being typically 10–18 Hz, but it will only be observed where the *gem* protons have different chemical shift positions, as discussed in sections 3.9.2 and 3.10.

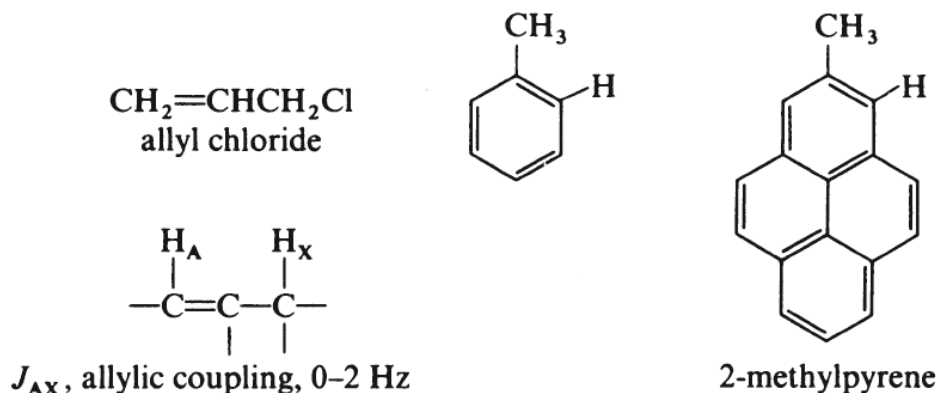
*Vicinal coupling* (three bonds separating the protons) varies from  $^3J = 0$  to  $^3J = 12$  Hz in rigid systems, but in freely rotating carbon chains (alkyl groups) it is usually around 8 Hz.

*Long-range coupling* in alkane systems (extending over more than three bonds—that is,  $^4J$  and longer) is usually vanishingly small, but is observed within rigid systems where the W-shaped zig-zag of bonds is near to being coplanar, as indicated by the heavy bonds in the formulae at the bottom of table 3.10.

*Trans coupling* in alkene groups ( $^3J$ , 11–19 Hz) is stronger than *cis* coupling ( $J$ , 5–14 Hz). Typical values, 16 Hz and 8 Hz, respectively.

*Aromatic coupling* depends on whether the coupling protons are *ortho*, *meta* or *para* to each other, and in simple cases the coupling constant is definitive in deciding the orientation; thus,  $^3J_{ortho}$ , 7–10 Hz;  $^4J_{meta}$ , 2–3 Hz;  $^5J_{para}$ , 0–1 Hz.

*Allylic coupling*, as in allyl chloride, is the most likely four-bond coupling to be met in nonaromatic molecules and is very small ( $^4J$ , 0–2 Hz). The analogous coupling in aromatic systems (for example, between the methyl protons and the *ortho* protons in the ring) is not normally large enough to be measured, although it has been observed in certain polynuclear aromatic hydrocarbons, such as 2-methylpyrene, in which considerable double-bond character exists in the intervening aromatic  $\text{C}=\text{C}$  bond.



### 3.9.2 FACTORS INFLUENCING GEMINAL COUPLING

The electronegativity of an attached substituent alters the values of *gem* coupling, but not always predictably. In groups such as  $-\text{CH}_2-\text{X}$  the *gem* coupling will range from 12 Hz to 9 Hz as the electronegativity of X is increased. These couplings cannot usually be measured directly, because the two protons will have identical  $\delta$  values unless they are diastereotopic, but in the derived  $-\text{CHD}-\text{X}$  the *gem* coupling between H and D ( $\text{H}-\text{C}-\text{D}$ ) can be measured;  $J_{\text{H,H}}$  can then be calculated from the equation  $J_{\text{H,H}} = 6.53J_{\text{H,D}}$  (see section 3.9.4).

The magnitude of  $J_{\text{gem}}$  also varies with the  $\text{C}-\hat{\text{C}}-\text{C}$  bond angle, being of greatest magnitude (10–14 Hz) in the strain-free cyclohexanes and cyclopentanes. With increasing angular strain the value of  $J_{\text{gem}}$  drops, being 8–14 Hz in cyclobutanes and 4–9 Hz in cyclopropanes.

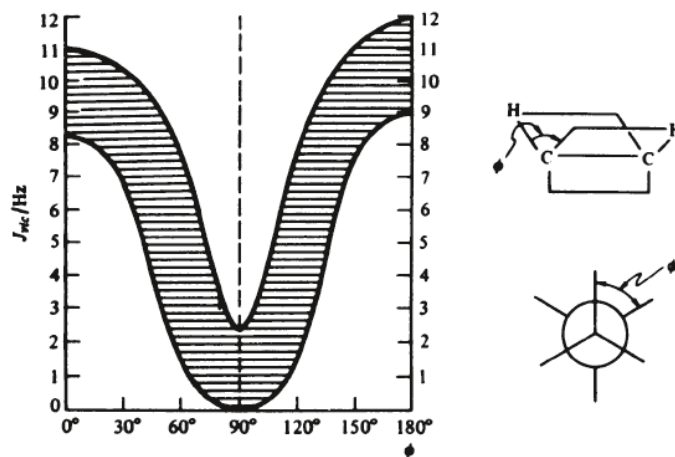
### 3.9.3 FACTORS INFLUENCING VICINAL COUPLING

The electronegativity of attached substituents alters the value of vicinal coupling, as it does that of geminal coupling. In qualitative terms, the more electronegative the substituent the smaller the value of  $J_{\text{vic}}$ , so that in unhindered ethanes the value is  $\approx 8$  Hz and in halogenoethanes it is lowered to 6–7 Hz. Where there is restricted rotation, the angle subtended by the electronegative substituent at the  $\text{C}-\text{C}$  bond also has an effect on  $J_{\text{vic}}$ , and other constraints which alter the angles  $\text{H}-\hat{\text{C}}-\text{C}$  and  $\text{C}-\hat{\text{C}}-\text{H}$ , particularly the presence of small rings, will influence  $J_{\text{vic}}$ .



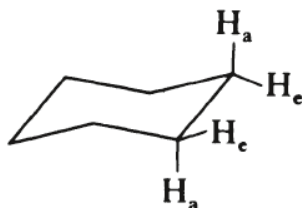
### Karplus's equations

$$\begin{aligned}\phi \text{ between } 0^\circ \text{ and } 90^\circ: J_{vic} &= 8.5 \cos^2 \phi - 0.28 \\ \phi \text{ between } 90^\circ \text{ and } 180^\circ: J_{vic} &= 9.5 \cos^2 \phi - 0.28\end{aligned}$$



**Figure 3.23** Variation of vicinal coupling constant,  $J_{vic}$ , with dihedral angle  $\phi$  (graphical presentation of Karplus's equations).

As an example of the successful application of these rules, we can consider the protons in chair cyclohexanes: diaxial protons have coupling constants around 10–13 Hz (somewhat larger than predicted) and this collates with their  $180^\circ$  orientation; diequatorial protons, or those with axial/equatorial relationship, have coupling constants around 2–5 Hz, corresponding to about  $60^\circ$  orientation.

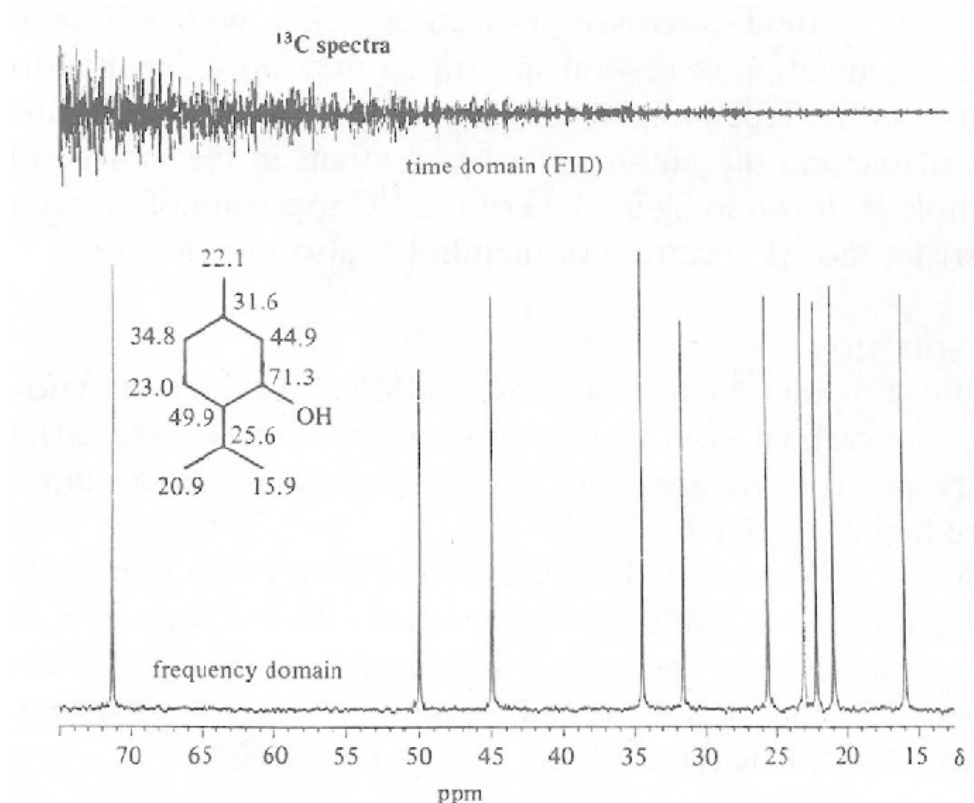


## CARBON-13 NMR SPECTROSCOPY

In a 1.9 T field the precession frequency of  $^{13}\text{C}$  is 20 MHz, that for  $^1\text{H}$  being 80 MHz and  $^{12}\text{C}$  being nonmagnetic. In principle, therefore, it is not difficult to observe  $^{13}\text{C}$  NMR. The magnetic moment of  $^{13}\text{C}$  is about one-quarter that of  $^1\text{H}$ , so that signals are inherently weaker, but the overwhelming problem is that the natural abundance of  $^{13}\text{C}$  is only 1.1 per cent. The problem in simple molecules can be overcome by synthesizing  $^{13}\text{C}$ -enriched samples, but this is of little value in complex molecules.

### 3.13.2 MULTIPLICITY

Both  $^{13}\text{C}$  and  $^1\text{H}$  have  $I = \frac{1}{2}$ , so that we should expect to see coupling in the spectrum between (a)  $^{13}\text{C}—^{13}\text{C}$  and (b)  $^{13}\text{C}—^1\text{H}$ . The probability of two  $^{13}\text{C}$  atoms being together in the same molecule is so low that  $^{13}\text{C}—^{13}\text{C}$  couplings are not usually observed. Couplings from  $^{13}\text{C}—^1\text{H}$  interaction have already been discussed (page 156) and these couplings should be observed in the  $^{13}\text{C}$  spectra. However, these couplings make the  $^{13}\text{C}$  spectra extremely complex, and they have been eliminated by decoupling. The proton-coupled (or non-decoupled) spectrum is shown in figure 3.33.



## 3.14 STRUCTURAL APPLICATIONS OF $^{13}\text{C}$ NMR

Differentiation among alternative organic structures has a long history in  $^1\text{H}$  NMR and it is substantially extended by  $^{13}\text{C}$  NMR. Increased shift resolution (compared with  $^1\text{H}$  spectra) is often sufficient in itself to lead to correct structural assignment, but the use of correlation data for chemical shift positions and the calculation of multiplicity in non-decoupled spectra both have their contributions to make. Figure 3.35 shows the approximate chemical shift positions for common organic functional groups; the shifts are measured in ppm from TMS as standard.

### 3.15 CORRELATION DATA FOR $^{13}\text{C}$ NMR SPECTRA

While it is possible to offer reasonable rationales for proton NMR chemical shifts (section 3.4), the explanation of carbon-13 NMR chemical shifts is much less self-consistent, despite extensive studies; happily, predictions based on the tables of empirical data which follow are very reliable.

It is usually very difficult to deduce *a priori* the structure of an organic molecule from its  $^{13}\text{C}$  NMR spectrum; indeed, this would be at variance with experimental experience, where much other information is often simultaneously available—both chemical and spectroscopic (IR, UV, MS and proton NMR spectra). Proof of structure usually involves hypothesizing what the likely structures for the compound are, and then using the

tables to predict *for each of these possibilities* the appearance of the  $^{13}\text{C}$  NMR spectrum, and that structure which gives the best fit with observed values is likely to be correct.

Some general features should be given consideration.

#### *sp<sup>3</sup> hybridized carbons*

Figure 3.35 shows that  $\text{sp}^3$  carbons come to resonance in the range  $\delta$  0–80; within this overall range, it is worth noting that the carbons of C—O bonds, C—N bonds and C—S bonds appear in the narrower ranges indicated. Exceptions abound, usually as a consequence of influential electronic or steric effects. An extreme and interesting exception is the signal for the carbon atom in tetraiodomethane,  $\text{CI}_4$ , at  $\delta$  –300 (that is, at 300 ppm *lower* frequency than TMS).

#### *sp<sup>2</sup> hybridized carbons*

Alkene and aromatic carbon atoms give signals in overlapped areas of the spectrum ( $\delta$  80–150 and  $\delta$  110–140, respectively)—a fact which can make their distinction less clear than in the proton NMR spectrum. The great diversity of C=O groups is mirrored in their significantly differing shift positions (see table 3.17). A less common  $\text{sp}^2$  class (not shown in figure 3.35) is in the C=N group of aromatic imines, often called *Schiff's bases*; the range is  $\delta$  130–150. (Aliphatic imines are unstable and tend to decompose or polymerize.)

#### *sp hybridized carbons*

For the  $\text{sp}$  carbons of alkynes, nitriles and isonitriles, the shift ranges are usefully narrow (see figure 3.35).

Each main class of carbon environment ( $\text{sp}^3$ ,  $\text{sp}^2$  and  $\text{sp}$ ) will be discussed, showing how the effects of further substitutions can be predicted.

*The first steps in deducing the structure of an organic compound, using the  $^{13}\text{C}$  NMR spectrum, are:*

1. Count the number of signals in the spectrum; this is the number of nonequivalent carbon environments in the molecule. (Identify and discount the signal(s) from solvent; see table 3.19.)
2. Use figure 3.35 to assign signals approximately to the regions  $\delta$  0–80,  $\delta$  80–150 and  $\delta$  160–220 (carbonyl carbons).
3. Note the intensities of the peaks: non-proton-bearing carbons give lower intensity signals, and groups of two or more equivalent carbons give higher intensity signals.
4. Take account of any multiplicity information (q, t, d or s).
5. Use the Correlation Tables (section 3.16.1) to predict the chemical shifts of all carbons in each putative structure.

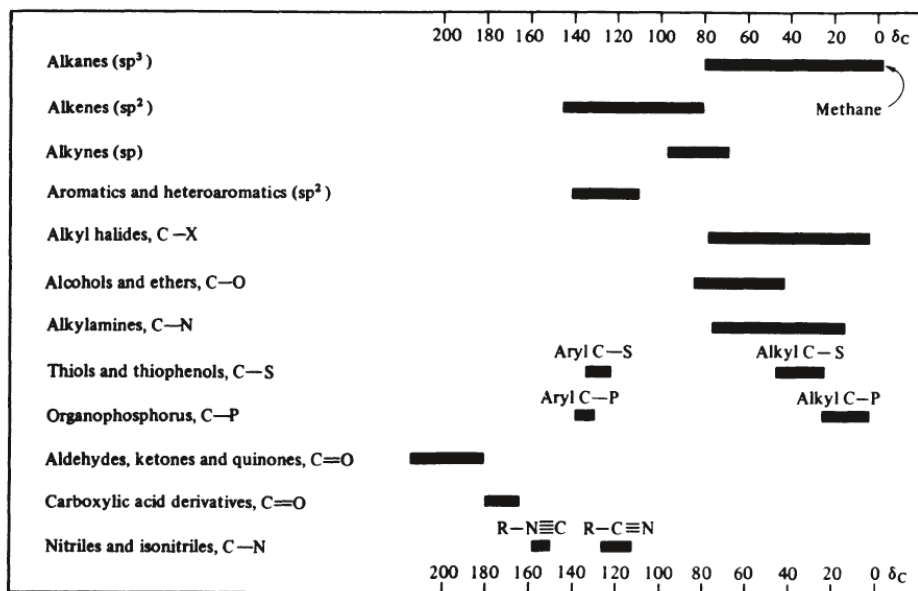


Figure 3.35  $^{13}\text{C}$  chemical shift summary chart ( $\delta$  values).

### Nuclear Overhauser Effect

The nuclear Overhauser effect can be used to demonstrate that two protons (or groups of protons) are in close proximity within the molecule, and is therefore of considerable value in the study of molecular geometry.

The basic observation of NOE can be described by reference to the hypothetical molecule I. The two protons,  $H_a$  and  $H_b$ , we must imagine to be close enough to allow through-space interaction of their fluctuating magnetic vectors; each can contribute to the other's spin–lattice relaxation process ( $T_1$ ). The number of intervening bonds between  $H_a$  and  $H_b$  is too large to allow normal coupling between them, but this is not a prerequisite for the operation of NOE.

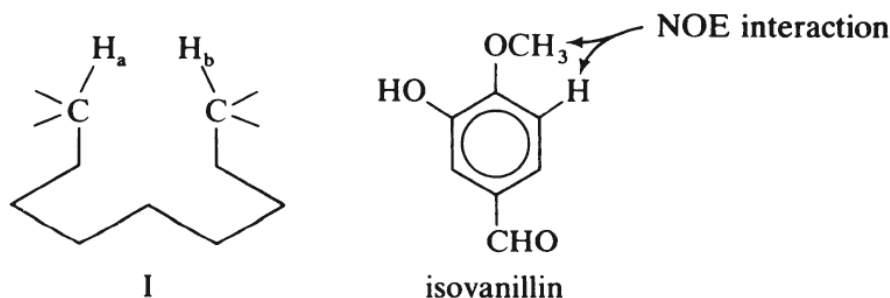


If we double irradiate at the  $H_b$  signal, we shall stimulate absorption and emission processes for  $H_b$ , and this stimulation will be transferred through space to the relaxation mechanism of  $H_a$ . The spin-lattice relaxation of  $H_a$  will be speeded up, leading to a net increase in the NMR absorption signal of  $H_a$ .  $H_a$  and  $H_b$  must be within 3.5 Å of each other.

In summary, provided that  $H_b$  makes a significant contribution to the spin-lattice relaxation process of  $H_a$ , then double irradiation of  $H_b$  causes an increase in the intensity of the  $H_a$  signal (by 1–50% for protons).

Since molecular oxygen is paramagnetic, and can contribute to nuclear spin-lattice relaxation processes, the NOE experiment should be carried out on deoxygenated samples, to avoid interference with the NOE observation.

A simple example of NOE is found in isovanillin. If we first record the NMR spectrum for isovanillin normally, and then while irradiating at the  $\text{CH}_3\text{O}$  frequency, the integral for the *ortho* proton (which appears as a doublet) is markedly increased.



A practical consequence of NOE is that in spin decoupling experiments the line intensities observed on a decoupled spectrum may not be the same as in the normal (nondecoupled) spectrum, and these intensities may not always correspond to integral numbers of protons. This same observation applies in the proton-decoupled spectra of  $^{13}\text{C}$  resonances (see page 179).

The NOE can be more carefully assessed with difference spectra, in which a spectrum is first recorded without double irradiation, and then with double irradiation of one proton, or group of protons: subtraction of the former from the latter leaves residues of signals only where that signal from a nearby proton has been NOE enhanced, since all other signals will cancel out. The method has been used to establish the stereochemistry of many complex biological molecules, and also some simple *E* and *Z* alkene isomers. The most reliable results are obtained where both *E* and *Z* isomers are available; the NOE difference spectrum showing the greatest

enhancement can be taken to be the isomer in which the groups are closer together in space.

### 3S.3.3 2D NMR—shift correlation spectra—COSY

The ability to present computed data in 'three dimensions' rests very much with graphics software, permitting such stack-plots as are shown (in a different context) in figure 4.3. Alternatively, the same information can be presented in cross-section, effectively a contour map of the peaks.

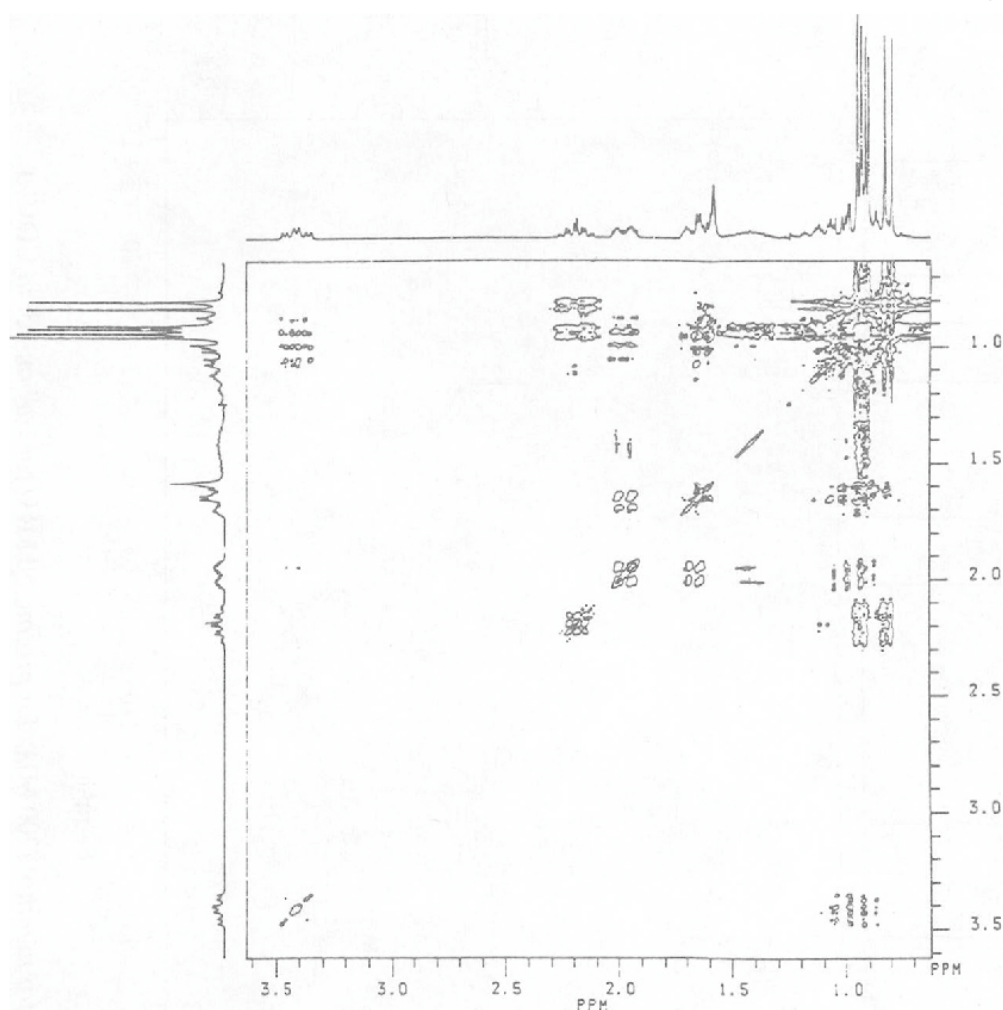
A conventional NMR spectrum is a plot of intensity against frequency, but for coupling nuclei (H—H or C—H, etc.) their interactions are also time-variable, as discussed above; by sampling these interactions as a function of time (and, hence, frequency) it is possible to separate out the interactions among (for example) the carbons and hydrogens of organic functions in such a way as to establish which protons couple with which carbons, or else which protons couple with which other protons. Since two frequency axes are involved, the method is called *two-dimensional NMR*, but the information is plotted in pseudo-three-dimensional form, with intensity as the third dimension as in figures 3.47 and 3.48.

There have been very many variations published using 2-D NMR, and these are dealt with in the specialist texts listed in 'Further Reading', but two of the most important are examples of *correlation spectroscopy*, either homonuclear or heteronuclear. The original use of the acronym COSY referred to the homonuclear proton-proton case; the important heteronuclear carbon-proton correlation case is not usually referred to as COSY, but this deserves to be so defined.

Figures 3.47 and 3.48 illustrate these for the molecule of menthol; it will be instructive to compare these frequently with figures 3.30 and 3.46.

*Proton-proton correlation spectroscopy* (homonuclear COSY, figure 3.47) sets out the proton NMR spectrum of an organic molecule such as menthol along the x axis, and repeats it along the y axis, with the signals repeated yet again in the contours of the *diagonal peaks*; wherever a proton couples with another proton (that is, wherever correlation is established), this is indicated by the contour of an off-diagonal *cross-peak*. The interpretation of the COSY spectrum is best carried out with the help of the DEPT spectrum in figure 3.46 and in conjunction with an analysis of the C—H correlation spectrum in figure 3.48.





**Figure 3.47** *Homonuclear proton–proton shift correlation spectrum, COSY, for menthol (200 MHz in  $\text{CDCl}_3$ ). A cross-peak establishes correlation with a diagonal peak.*

### An Overview of the HETCOR Experiment

As we did in the COSY experiment, we want to allow the magnetization vectors of the protons to precess according to different rates, as dictated by their chemical shifts. Therefore, we apply a  $90^\circ$  pulse to the protons, then include an evolution time ( $t_1$ ). This pulse tips the bulk magnetization vector into the  $X'Y'$  plane. During the evolution period, the proton spins precess at a rate determined by their chemical shifts and the coupling to other nuclei (both protons and carbons). Protons bound to  $^{13}\text{C}$  atoms experience not only their own chemical shifts during  $t_1$  but also homonuclear spin coupling and heteronuclear spin coupling to the attached  $^{13}\text{C}$  atoms. It is the interaction between  $^1\text{H}$  nuclei and  $^{13}\text{C}$  nuclei that produces the correlation that interests us. After the evolution time, we apply simultaneous  $90^\circ$  pulses to both the protons and the carbons. These pulses transfer magnetization from protons to carbons. Since the carbon magnetization was “labeled” by the proton precession frequencies during  $t_1$ , the  $^{13}\text{C}$  signals that are detected during  $t_2$  are modulated by the chemical shifts of the coupled protons. The  $^{13}\text{C}$  magnetization can then be detected in  $t_2$  to identify a particular carbon carrying each type of proton modulation.

A HETCOR experiment, like all two-dimensional experiments, describes the environment of the nuclei during  $t_1$ . Because of the manner in which the HETCOR pulse sequence has been constructed, the only interactions that are responsible for modulating the proton spin states are the proton chemical shifts and homonuclear couplings. Each  $^{13}\text{C}$  atom may have one or more peaks appearing on the  $f_2$  axis that correspond to its chemical shift. The proton chemical shift modulation causes the two-dimensional intensity of the proton signal to appear at an  $f_1$  value that corresponds to the proton chemical shift. Further proton modulations of much smaller frequency arise from homonuclear (H–H) couplings. These provide fine structure on the peaks along the  $f_1$  axis. We can interpret the fine structure exactly as we would in a normal proton spectrum, but in this case we understand that the proton chemical shift value belongs to a proton that is attached to a specific  $^{13}\text{C}$  nucleus that appears at its own carbon chemical shift value.

We can thus assign carbon atoms on the basis of known proton chemical shifts, or we can assign protons on the basis of known carbon chemical shifts. For example, we might have a crowded proton spectrum but a carbon spectrum that is well resolved (or vice versa). This approach makes the HETCOR experiment particularly useful in the interpretation of the spectra of large, complex molecules. An even more powerful technique is to use results from both the HETCOR and COSY experiments together.

**Combined usage of IR, UV, NMR and Mass spectrometric data for structure elucidation of organic compounds having medium complexity**

Structure elucidations of problems **1-250** from the book of ‘Organic Structures from Spectra, 4<sup>th</sup> Edition by L.D. Field, S. Sternhell and J. R. Kalman.

## *Class Tests*

**Class Test:1**

Describe rules for splitting of proton signals in  $^1\text{H}$ NMR.

**Class Test:2**

Describe factors influencing coupling constants in  $^1\text{H}$ NMR.

**Class Test:3**

Elucidate structures of following compounds based on provided spectral data:

<b>a) <math>\text{C}_3\text{H}_5\text{Cl}_3</math></b> singlet, $\delta$ 2.2, 3H singlet, $\delta$ 4.0, 2H	<b>b) <math>\text{C}_5\text{H}_{10}\text{Br}_2</math></b> doublet, $\delta$ 0.9, 6H multiplet, $\delta$ 1.5, 1H triplet, $\delta$ 1.85, 2H triplet, $\delta$ 5.3, 1H
<b>c) <math>\text{C}_3\text{H}_8\text{O}</math></b> IR: broad peak near $3400\text{ cm}^{-1}$ nmr: doublet, $\delta$ 1.2, 6H broad singlet, $\delta$ 2.0, 1H septet, $\delta$ 4.0, 1H	<b>d) <math>\text{C}_{10}\text{H}_{12}\text{O}</math></b> IR: peak at $1710\text{ cm}^{-1}$ nmr: singlet, $\delta$ 2.1, 3H multiplet, $\delta$ 3.0, 4H multiplet, $\delta$ 7.1, 5H
<b>e) <math>\text{C}_5\text{H}_{10}</math></b> triplet, $\delta$ 0.9, 3H multiplet, $\delta$ 1.5, 2H quartet, $\delta$ 2.1, 2H multiplet, $\delta$ 4.8, 1H multiplet, $\delta$ 5.1, 1H multiplet, $\delta$ 5.8, 1H	

## *Assignments*

### Assignment:1

Determine the structures of seven isomers of  $\text{C}_5\text{H}_{10}\text{O}$  using  $^1\text{H}$ NMR data:

1. **Compound A:**  $\delta$  2.38 t (2H), 2.1 s (3H), 1.58 sext (2H), 0.9 t (3H)
2. **Compound B:**  $\delta$  9.8 t (1H), 2.32 dd (2H), 2.23 m (1H), 1.0 d (6H)
3. **Compound C:**  $\delta$  9.78 s (1H), 2.45 t (2H), 1.64 quin (2H), 1.38 sext (2H), 0.95 t (3H)
4. **Compound D:**  $\delta$  2.43 q (4H), 1.05 t (6H)
5. **Compound E:**  $\delta$  9.64 d (1H), 2.29 sext (2H), 1.47 m (1H), 1.77 m (1H), 1.11 d (3H), 0.97 t (3H)
6. **Compound F:**  $\delta$  2.59 sept (1H), 2.14 s (3H), 1.1 d (6H)
7. **Compound G:**  $\delta$  9.5 s (1H), 1.1 s (9H)

### Assignment:2

Why chemical shifts of diastereotopic protons in  $^1\text{H}$ NMR are different as compare to any enantiotopic and homotopic proton, explain with examples?



## **Class Presentations**

## **Topics for Presentations**

**(BS- VIII Semester)**

1.	Basic concepts behind electronic transitions
2.	Lambert-Beer's law and its applications
3.	Woodward rules and its applications
4.	Basic Concept behind IR spectroscopy and its absorption mechanism
5.	Factors affecting the IR absorption frequencies
6.	Basic concepts behind mass spectrometry and its ionization techniques
7.	Mass fragmentation patterns in structural elucidation
8.	Basic Concepts behind NMR
9.	Factors affecting chemical shifts in NMR

**Mid-Semester/Final Exam Question Paper**

# The Islamia University of Bahawalpur

## Department of Chemistry



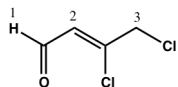
### BS (Semester VIII)- Course (CHEM-02843) Organic Spectroscopy; Mid Term Examination

<b>Total Marks 30</b>	<b>Time Allowed: 75 min</b>
<b>NOTE:</b> Time allowed will be strictly observed. You will have to hand over answer sheet (MCQs) after 20 min and before getting the next part of the question paper and its answer sheet.	
<b>Name of the Candidate and Roll No.</b>	

#### PART-I (MCQs) Pick the best answer

(Marks 10)

- What is the order of decreasing vibrational frequency for C—Cl, C—Br, C—C, C—O and C—H?
  - C-H, C-C, C-O, C-Cl, C-Br
  - C-Cl, C-Br, C-C, C-H, C-O
  - C-O, C-H, C-Br, C-Cl, C-C
  - C-Br, C-Cl, C-C, C-O, C-H
- The wavelengths greater than .....cannot be detected by human eye:-
  - 600 nm
  - 700 nm
  - 800 nm
  - 400 nm
- What is the correct increasing order of stretching frequencies for  $C \equiv C$ ,  $C = C$  and  $C - C$ ?
  - $C - C > C = C > C \equiv C$
  - $C \equiv C > C = C > C - C$
  - $C - C > C = C < C \equiv C$
  - $C \equiv C < C - C > C = C$
- The vibrational energy of the bond in IR is directly proportional to the:
  - Mass
  - magnetic field
  - bond strength
  - Energy source
- Which of the following compounds has the MOST deshielded protons?
  - $CH_3Cl$
  - $CH_3I$
  - $CH_3Br$
  - $CH_4$
- How many kinds of  $^1H$ NMR signals will be observed for 2-methylpropene?
  - 1
  - 4
  - 5
  - 2
- Which of the following compounds has the MOST deshielded methyl protons?
  - tetramethylsilane
  - methanol
  - methyl fluoride
  - methylamine
- Arrange the following compounds in order of decreasing chemical shift for the underlined hydrogens (largest  $\delta$  value first, smallest value last)
  - $CH_3CH_3\text{CH}_3$
  - $CH_3O\text{CH}_2\text{CH}_3$
  - $Cl_2CH\text{CH}_2\text{CH}_3$
  - $ClCH_2\text{CH}_2\text{CH}_3$
  - $ii > iii > iv > i$
  - $ii > iii > i > iv$
  - $iii > ii > i > iv$
  - $iii > ii > iv > i$
- The signal for the methylene protons of n-butane is split into a:
  - doublet
  - triplet
  - quartet
  - quintet
- Reading from left to right, what multiplicity would be found for the three nonequivalent sets of protons in the  $^1H$  NMR spectrum of the following compound?



- s, s, s
- s, s, d
- s, d, d
- d, d, s

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BS (Semester VIII)- Course (CHEM-02843)  
Organic Spectroscopy; Mid Term Examination

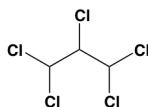
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### PART-II

(Marks 10)

Q. No. 2 Write short answers to following questions

1. What arrangement of protons would give two triplets of equal area? (2 marks)
2. What spectrum would you expect for the following molecule? (2 marks)



3. A proton resonates at 144 Hz on 60 MHz instrument, calculate  $\delta$  ppm of that proton? (2 marks)
4. How could IR spectroscopy distinguish among 1-hexyne, and 2-hexyne? (2 marks)
5. The  $^1\text{H}$ NMR spectrum of a compound with molecular formula  $\text{C}_8\text{H}_6\text{O}_2$  has two singlets with an area ratio of 1:2, draw its structure. (2 marks)

### PART-III

(Marks 10)

1. Discuss various factors that influence chemical shifts in NMR spectroscopy (6 marks)
2. Why coupling constants are important in  $^1\text{H}$ NMR? (4 marks)

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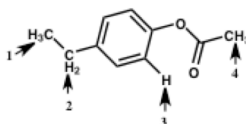


**BS (Semester VIII)- Course (CHEM-02843)**  
**Organic Spectroscopy; Final Term Examination**

Total Marks 50	Time Allowed: 120 min
<b>NOTE:</b> Time allowed will be strictly observed. You will have to hand over answer sheet (MCQs) after 30 min and before getting the next part of the question paper and its answer sheet.	
<b>Name of the Candidate and Roll No.</b>	

**PART-I (MCQs) Pick the best answer (Marks 20)**

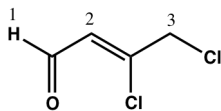
1. Which of the indicated proton(s) is (are) the most shielded (lowest value of  $\delta$ )?



- a. 1                      b. 2                      c. 3                      d. 4
2. Which is (are) the least shielded in aforementioned compound?  
a. 1                      b. 2                      c. 3                      d. 4
3. Which 2D technique in NMR helps to determine stereochemistry?  
a. COSY                      b. NOESY                      c. HSQC                      d. HMBC
4. In mass spectrometry the most abundant +ive charge fragments are:  
a. favored                      b. scant                      c. disfavored                      d. both b & c
5. The most predictable fragmentation in mass spectrometry is due to  
a. Two bonds cleavage                      b. Inductive cleavage                      c. McLafferty rearrangement                      d.  $\alpha$ -cleavage
6. Which carbon of hex-3-en-2-one shows the most downfield chemical shift in the NMR spectrum?  
a. C1                      b. C2                      c. C4                      d. C6
7. What is plotted along the x-axis of a EI spectrum?  
a. mass/energy                      b. mass X charge                      c. mass                      d. mass/charge
8. What is the splitting pattern of the methylene protons in propane?  
a. septet                      b. doublet                      c. triplet                      d. quartet
9. Which of the following compounds has the MOST deshielded methyl protons?  
a. tetramethylsilane                      b. methanol                      c. methyl fluoride                      d. methylamine
10. How many signals does the unsaturated ketone  $(\text{CH}_3)_2\text{CHCH}_2\text{C}(\text{O})\text{CH}=\text{CH}_2$  have in  $^1\text{H}$  NMR and  $^{13}\text{C}$  NMR spectra?  
a. six  $^1\text{H}$  signals and six  $^{13}\text{C}$  signals                      b. three  $^1\text{H}$  signals and four  $^{13}\text{C}$  signals



- c. five  $^1\text{H}$  signals and four  $^{13}\text{C}$  signals      d. three  $^1\text{H}$  signals and five  $^{13}\text{C}$  signals
11. Which of the following processes leads to the absorption of infrared radiation by a molecule?  
 a. bond breaking    b. nuclear spin flip    c. electron excitation    d. bond vibration
12. Reading from left to right, what multiplicity would be found for the three nonequivalent sets of protons in the  $^1\text{H}$  NMR spectrum of the following compound?



- a. s, s, s      b. s, s, d      c. s, d, d      d. d, d, s
13. Arrange following compounds in order of decreasing chemical shift for the underlined hydrogens:-  
 1)  $\text{CH}_3\text{CH}_2\text{CH}_3$     2)  $\text{CH}_3\text{OCH}_2\text{CH}_3$     3)  $\text{Cl}_2\text{CHCH}_2\text{CH}_3$     4)  $\text{ClCH}_2\text{CH}_2\text{CH}_3$
- a.  $2 > 3 > 1 > 4$     b.  $2 > 3 > 4 > 1$     c.  $3 > 2 > 1 > 4$     d.  $3 > 2 > 4 > 1$
14. A compound of formula  $\text{C}_5\text{H}_{12}$  gives 1 signals in  $^1\text{H}$  NMR and 2 signals in  $^{13}\text{C}$  NMR. The compound is:-  
 a. Pentane    b. 2-Methylbutane    c. 2,2-Dimethylpropane    d. None
15. Which of the following is the definition of the base peak in a mass spectrum?  
 a. The peak corresponding to the molecular ion    b. The peak corresponding to the ion with lowest  $m/z$   
 c. The peak corresponding to the most abundant ion    d. The peak corresponding to the any fragment ion
16. What is the mass of the most abundant cation formed by N,N-dimethylbutylamine  $[(\text{CH}_3)_2\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3]^+$ ?  
 a.  $m/z$  86    b.  $m/z$  43    c.  $m/z$  58    d.  $m/z$  101
17. The molecule  $\text{HOCH}_2\text{CH}_2\text{OH}$  will have a  $^1\text{H}$ NMR spectrum consisting of...  
 a. two singlets    b. a triplet and a doublet    c. two doublets    d. a singlet and a doublet
18. The natural abundance of  $^{13}\text{C}$  is about:  
 a. Four times less than  $^1\text{H}$     b. 0.11% of total carbon    c. 1.1% of total carbon    d. 99% of total carbon
19. Which of the following regions in the electromagnetic spectrum corresponds to the radiation with highest energy?  
 a. Ultraviolet    b. Infrared    c. Visible    d. Radio waves
20. The Heteronuclear Single Quantum Coherence (HSQC) is used to find:  
 a. long range  $^1\text{H}$ - $^1\text{H}$  connectivity    b. long rang  $^1\text{H}$ - $^{13}\text{C}$  connectivity  
 c. direct  $^1\text{H}$ - $^{13}\text{C}$  connectivity    d. long range  $^1\text{H}$ - $^{14}\text{N}$  connectivity



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**Department of Chemistry**

**BS (Semester VIII)- Course (CHEM-02843)**  
**Organic Spectroscopy; Final Term Examination 19 June 2018**

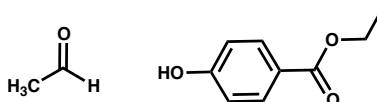
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**PART-II**

**(Marks 16)**

**Q. No. 2 Write short answers to following questions**

1. Describe rule of thirteen in mass spectrometry? (2 marks)
2. How can you distinguish 1-chlorobenzene from 1-bromobenzene in mass spectrometry? (2 marks)
3. Determine the structure for a compound of formula  $C_5H_{10}Br_2$  with following  $^1H$ -NMR data:  $\delta$  0.9 d (6H), 1.5 m (1H), 1.85 dd (2H), 5.3 t (1H) (2 marks)
4. Assign chemical shifts of each proton in the above structure. (2 marks)
5. Show interactions of above compound (in question # 3) between protons resonating at 5.3 and 1.85 in COSY spectrum (2 marks)
6. Describe inductive cleavage in mass spectrometry. (2 marks)
7. Predict base peak of following compounds in mass spectrometry? (2 marks)

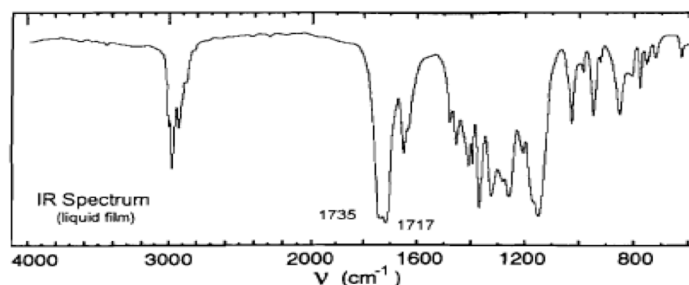


8. What spectroscopic techniques can be used to determine stereochemistry of organic compounds? (2 marks)

### PART-III

(Marks 14)

1. The labels of 2-bromo benzoic acid, 3-bromo benzoic acid and 4-bromo benzoic acid bottles got mixed. How can you characterize them using some spectrometric method? (4 marks)
2. Elucidate structure of following unknown compound with the help of provided spectra and justify your findings: (10 marks)



No significant UV absorption above 220 nm

