CHAPTER 18

NUCLEAR MAGNETIC RESONANCE (NMR) SPECTROSCOPY

18.1 Introduction

Nuclear Magnetic resonance (NMR) is a powerful and theoretically complex tool. *The study of absorption of radio frequency radiation by a magnetic nucleus in the presence of an applied field is called* **nuclear magnetic resonance,** *often abbreviated as NMR.* NMR spectroscopy can provide detailed and quantitative determination on the functional groups, topology, dynamic and three dimensional structures of molecules in solution and the solid state. Since the area under an NMR peak is usually proportional to the number of spins involved, peak integrals can be used to determine composition quantitatively.

Structure and molecular dynamics can be studied (with or without "magnetic angle" spinning (MAS) by NMR of quadrupolar nuclei (that is, with spin $S > \frac{1}{2}$ even in the presence of magnetic "dipole-dipole" interaction broadening (or simply, dipolar broadening) which is always much smaller than the quadrupolar interaction strength because it is a magnetic vs. an electric interaction effect.

Additional structural and chemical information may be obtained by performing double-quantum NMR experiments for pairs of spins or quadrupolar nuclei such as $^2H_2$.

Furthermore, nuclear magnetic resonance is one of the techniques that has been used to design quantum automata, an also build elementary *quantum computers*.

In simple words, NMR is one of the powerful techniques especially for

(i) Structural elucidation of organic compounds.

(ii) Determination of the nature of environment of practically all commonly occurring functional groups, as well as of fragments that are not otherwise accessible to other spectroscopic or analytical techniques.

(iii) Quantitative determination of compounds in mixtures and hence for studying the progress of chemical reactions.

(iv) Determination of kinetic and thermodynamic parameters for certain types of chemical processes.

(v) Determination of magnetic nuclei within molecules.

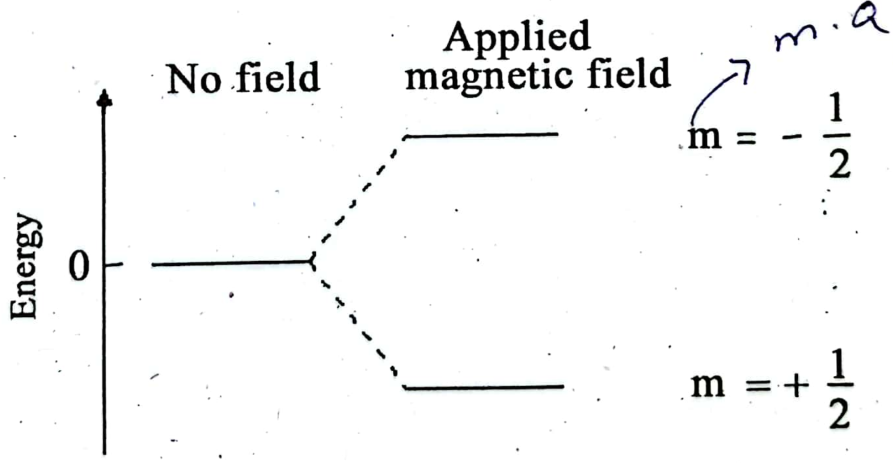
I - spin Net I = Sp. Q. no.

18.2 Nuclear spin and the splitting of energy levels in a magnetic field

Subatomic particles (electrons, protons and neutrons) can be imagined as spinning on their axes. In many atoms (such as ^{12}C) these spins are paired against each other, such that the nucleus of the atom has no overall spin. However, in some atoms (such as ^{1}H and ^{13}C) the nucleus does possess an overall spin. The rules for determining the net spin of a nucleus are as follows;

1. If the number of neutrons and the number of protons are both even, then the nucleus has no spin. e.g., ^{4}He, ^{12}C, ^{16}O, ^{32}S.
2. If the number of neutrons plus the number of protons is odd. then the nucleus has a half-integer spin (i.e. 1/2, 3/2. 5/2) ^{1}H, ^{15}N $(I = \frac{1}{2})$, ^{17}O $(I = 5/2)$, ^{35}Cl $(I = 3/2)$
3. If the number of neutrons and the number of protons are both odd. then the nucleus has an integer spin (i.e. I, 2, 3), e.g., ^{2}H, ^{14}N $(I = 1)$, ^{10}B $(I = 3)$ etc.

The overall spin.*l*. is important. Quantum mechanics tells us that a nucleus of spin *l* will have 2*l* + 1 possible orientations. A nucleus with spin 1/2 will have 2 possible orientations. In the absence of an external magnetic field, these orientations are of equal energy. If a magnetic field is applied, then the energy levels split. Each level is given a *magnetic quantum number, m*.



m.Q.no (Energy level split)

Fig.18.1 Energy levels for a nucleus with spin quantum number 1/2.

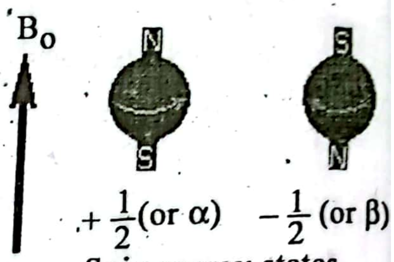
When the nucleus is in a magnetic field, the initial populations of the energy levels are determined by thermodynamics, as described by the Boltzmann distribution. This is very important, and it means that **the lower energy level will contain slightly more nuclei than the higher level.** It is possible to excite these nuclei into the higher level with electromagnetic radiation. The frequency of radiation needed is determined by the difference in energy between the energy levels.

18.3 Principles of NMR

The following principles lead to the NMR phenomenon

1. A spinning charge generates a magnetic field, as shown by the animation on the right. The resulting spin-magnet has a magnetic moment μm proportional to the spin.

2. In the presence of an external magnetic field (B_0), two spin states exist, +1/2 and –1/2. The magnetic moment of the lower energy +1/2 state is aligned with the external field, but that of the higher energy –1/2 spin state is opposed to the external field. Note that the arrow representing the external field points north.



Spin energy states

3. The difference in energy between the two spin states is dependent on the external magnetic field strength, and is always very small. The following diagram illustrates that the two spin states have the same energy when the external field is zero, but diverge as the field increases. At a field equal to B_x a formula for the energy difference is given (remember I = 1/2 and μm is the magnetic moment of the nucleus in the field).

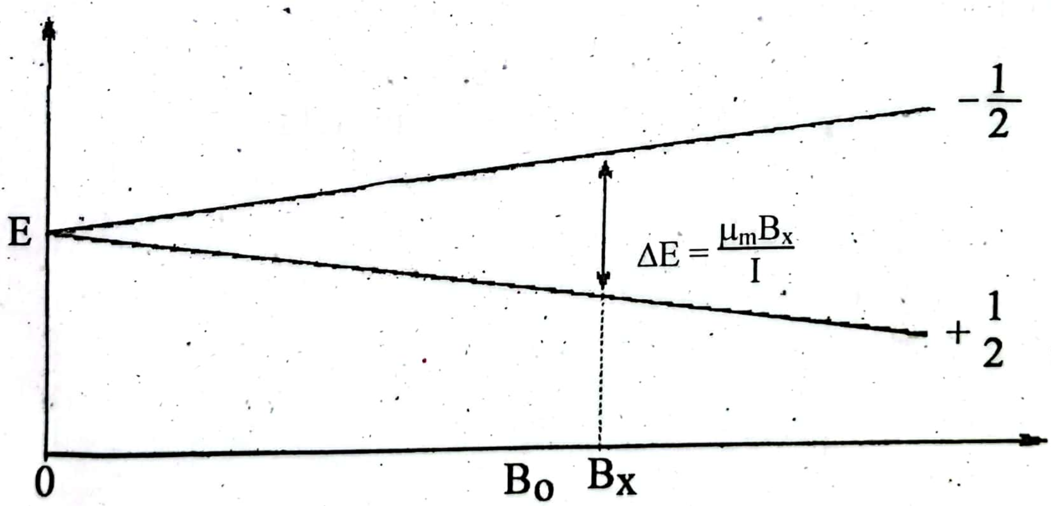


Fig. 18.2

Strong magnetic fields are necessary for NMR spectroscopy. The international unit for magnetic flux is the tesla (T). The earth's magnetic field is not constant, but is approximately 10^{-4} T at ground level. Modern NMR spectrometers use powerful magnets having fields of 1 to 20 T. Even with these high fields, the energy difference between the two spin states is less than

0.4184J/mole. To put this in perspective, recall that infrared transitions involve 4.184 to 40.184 J/mole and electronic transitions are nearly 100 time greater.

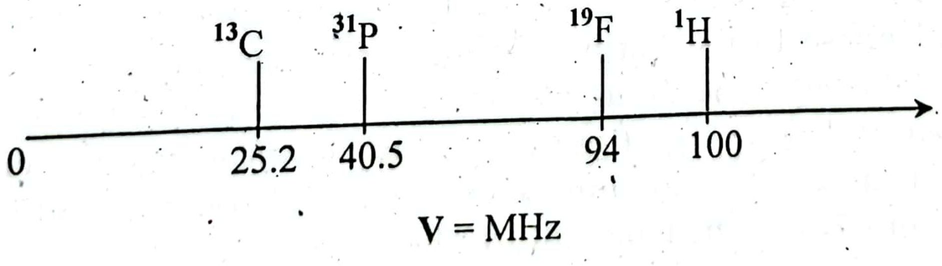
For NMR purposes, this small energy difference (ΔE) is usually given as a frequency in units of MHz (10^6 Hz), ranging from 20 to 900 Mz, depending on the magnetic field strength and the specific nucleus being studied.

Irradiation of a sample with radio frequency (rf) energy corresponding exactly to the spin state separation of a specific set of nuclei will cause excitation of those nuclei in the +1/2 state to the higher -1/2 spin state. Note that this electromagnetic radiation falls in the radio and television broadcast spectrum. NMR spectroscopy is therefore the energetically mildest probe used to examine the structure of molecules.

The nucleus of a hydrogen atom (the proton) has a magnetic moment μm=2.7927, and has been studied more than any other nucleus. The previous diagram may be changed to display energy differences for the proton spin states (as frequencies) by mouse clicking anywhere within it.

4. For spin 1/2 nuclei the energy difference between the two spin states at a given magnetic field strength will be proportional to their magnetic moments. For the four common nuclei noted above, the magnetic moments are $^{1}H\ \mu m = 2.7927$, $^{19}F\ \mu m = 2.6273$, $^{31}P\ \mu m = 1.1305$ and $^{13}C\ \mu m = 0.7022$. These moments are in nuclear magnetons, which are $5.05078.10^{-27}\ JT^{-2}$. The following diagram gives the approximate frequencies that correspond to the spin state energy separations for each of these nuclei in an external magnetic field of 2.35 T. The formula shows the direct correlation of frequency (energy difference) with magnetic moment (h = Planck's constant = $6.626069.10^{-34}$ Js).

$$B_o = 2.35T \qquad \nu = \frac{\mu B_o}{hI} = \frac{4.68\,\mu}{h}$$



18.4 NMR Spectroscopy Working

- Place the sample in a magnetic field.
- Excite the nuclei sample into nuclear magnetic resonance with the help of radio waves to produce NMR signals.

- These NMR signals are detected with sensitive radio receivers. The resonance frequency of an atom in a molecule is changed by the intramolecular magnetic field surrounding it.
- This gives details of a molecule's individual functional groups and its electronic structure.
- Nuclear magnetic resonance spectroscopy is a conclusive method of identifying monomolecular organic compounds. This method provides details of the reaction state, structure, chemical environment and dynamics of a molecule.

18.5 Relaxation Process

As the collection of nuclei continuously absorb radio frequency radiation the excess of nuclei originally in a lower state may diminish, accordingly the intensity of the absorption signal may diminish and may, under certain circumstances, vanish entirely. When the population in both states become equal, the phenomenon is referred to as **saturation**. A very lengthy time would be required for the initial excess of nuclei in a lower state to be reformed but other mechanisms that are simultaneously occurring reduce this considerably. *The various ways by which a nucleus returns to the lower energy level from the higher energy level without emitting radiation are known as* **relaxation process.** Two types of relaxation process involved in NMR are spin-spin relaxation and spin-lattice relaxation. Thus, it may be concluded that the lowest level is always more populated than the upper level. The intensity of NMR signal depends on the relative population of magnetic nuclei between magnetic quantum states.

Spin - lattice relaxation (T_1)

Nuclei in an NMR experiment are in a sample. The sample in which the nuclei are held is called the lattice. Nuclei in the lattice are in vibrational and rotational motion, which creates a complex magnetic field. The magnetic field caused by motion of nuclei within the lattice is called the lattice field. This lattice field hits many components. Some of these components will be equal in frequency and phase to the Larmor frequency of the nuclei of interest. These components of the lattice field can interact with nuclei in the higher energy state, and cause them to lose energy (returning to the lower state). The energy that a nucleus loses increases the amount of vibration and rotation within the lattice (resulting in a tiny rise in the temperature of the sample).

The relaxation time, T_1 (the average lifetime of nuclei in the higher energy state) is dependant on the magnetogyric ratio of the nucleus and the mobility of the lattice. As mobility increases, the vibrational and rotational frequencies increase, making it more likely for a component of the lattice field to be able to interact with excited nuclei. However, at extremely high mobilities, the probability of a component of the lattice field being able to interact with excited nuclei decreases.

Spin - spin relaxation (T_2)

Spin - spin relaxation describes the interaction between neighbouring nuclei with identical precessional frequencies but differing magnetic quantum states. In this situation, the nuclei can exchange quantum states: a nucleus in the lower energy level will be excited, while the excited nucleus relaxes to the lower energy state. There is no net change in the populations of the energy states, but the average lifetime of a nucleus in the excited state will decrease. This can result in line-broadening. This relaxation time is denoted as T_2 and its value is generally very small for crystalline solids or viscous liquids (~ 10^{-4} sec).

18.6 Technique Involved in NMR Spectroscopy

An experimental set up for NMR spectrometer is shown in Figure 18.3. The main components in an NMR instrument are:

(i) The magnet,
(ii) The field sweep generator,
(iii) The radio frequency source,
(iv) The signal detector and recorder system,
(v) The sample holder and probe.

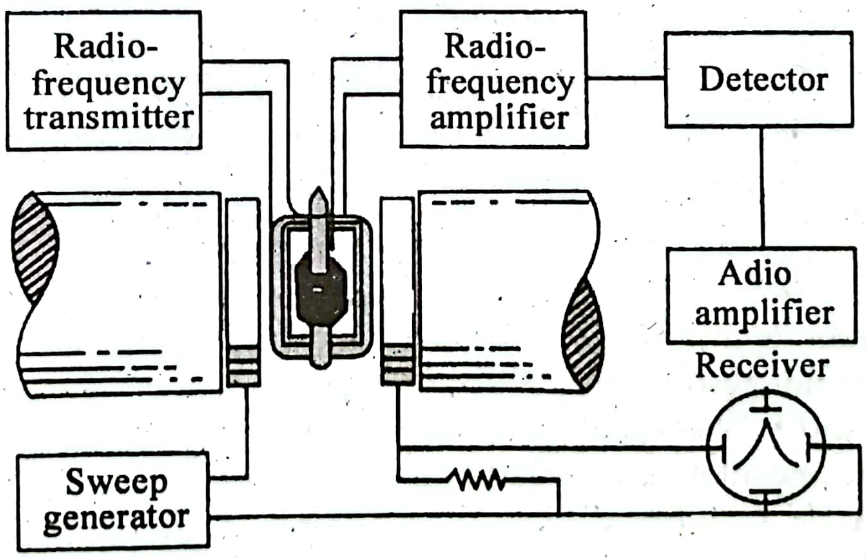


Fig.18.3 Experimental set-up for NMR

(i) The magnet

The accuracy and quality of an NMR instrument depends upon the strength of the magnet. Spectrometric magnets are of three types.

(a) **Permanent magnet:** Commercial magnet generates field of 7046 or 14092 G, corresponding to proton absorption sequencies of 30 and 60 MHz. Good thermostats are needed as the magnets are temperature sensitive.

(b) **Electromagnet:** Commercial magnet generates fields of 14,092, 21,140 and 23,490 G, corresponding to proton absorption frequencies of 60, 90 and 100 MHz. Such magnets need a cooling system.

(c) **Superconducting solenoid (supercon):** Fields as great as 110,390 G are attained, corresponding to a proton frequency of 470 MHz. This is used in the highest resolution instrument.

(ii) The field sweep generator

A pair of coils located parallel to the magnet faces as shown in Figure 18.3 permits alteration of the applied field over a small range. By varying a direct current through these coils, the effective Held can be changed by a few hundred milligauss without loss of field homogeneity.

(iii) The radio frequency source

The signal from a rf oscillator (transmitter) is fed into a pair of coils mounted at 90 degree to the path of the field. A fixed oscillator of exactly 60, 90 or 100 MHz is ordinarily employed.

(iv) The signal detector and recorder system

(v) Sample handling and sample holder

For a routine analysis, samples of about 5-50 mg are used. For high resolution work, samples must be in a non-viscous liquid state. Generally, solutions of the sample (2 to 15%) are employed.

The best solvent of proton NMR spectroscopy contains no protons. From this point, CCl_4 is ideal. The low solubility of many compounds in CCl_4 limits its value. However, a variety of duterated solvents are used instead. The most commonly used solvents are duterated chloroform, $CDCl_3$. duterated benzene C_6D_6, DMSO and D_2O.

The solution is introduced into the cell (often constructed of borosilicate glass which does not absorb rf radiation within the range in which the sample is expected to absorb). The usual NMR sample cell consists of a 5 mm outer diameter glass tube containing about 0.4 ml of solvent.

The solution should be free of paramagnetic and insoluble impurities. An internal reference compound (TMS) is added to the solution, and the tube is lowered into a probe placed between the poles of the magnet.

(vi) Probe

Probe is a device for holding the sample tube in a fixed spot in the field. It contains a sample holder, sweep source and detector coils. The detector and receiver coils are oriented at 90° to each other. The sample probe rotates the sample tube at a hundred r.p.m. on the longitudinal axis.

Working principle

The sample is placed between the poles of a huge electromagnet of adjusted field (10,000 to 15.000 gauss). Sweeper coils are used to adjust the field. The strong homogeneous magnetic field causes the nuclei to process. Radiant energy corresponding to radio frequency is then imposed with a radio frequency transmitter. When the applied frequency from the radio transmitter is equal to the Larmor frequency, the two are said to be in resonance. The net result of this resonance is that some nuclei are excited from the low energy (Mi= +1/2) state to the high energy state (M_1= –1/ 2) by absorption of energy from the source at a frequency equal to Larmor frequency. The (resonance frequency) at which the loss in energy from the transmitter occurs can be measured by using signal detector and device.

Presentation of NMR spectra

Resonance phenomenon can be achieved by either of the two ways: 1. By varying the frequency of oscillator keeping the external magnetic field constant, 2. by varying the external magnetic field keeping the frequency of the oscillator constant. In actual practice in most of the instruments a fixed frequency (usually 60 MHz) is supplied by a crystal controlled oscillator and the magnetic field applied to the sample is varied by an electromagnet. Thus the NMR spectrum of a compound is a plot of absorption of compound as a function of the external magnetic field. In a low resolution NMR spectrum (lower magnetic field strength), each kind of nucleus is characterized by a single absorption peak, the location of which appears to be independent of the chemical state of the atom. If. however the spectral region around one of the nuclear absorption peaks is examined in detail with a high resolution instruments (using higher magnetic field strength), the single peak is usually found to be composed of several peaks (known as multiplet). The position and the intensity of the component peaks depend critically upon the chemical environment of the nucleus responsible for the absorption. This dependence can be explained on the basis of

(i) Prediction of number of NMR signal
(ii) Chemical shift and
(iii) Spin-spin coupling (splitting).

These points are discussed below with reference to protons. NMR in the case of protons is referred to as PMR (or ^{1}HMR), i.e. Proton Magnetic Resonance.

18.7 Shielding and Deshielding of Protons

In the NMR spectrum of a compound, the electrons around the protons also play their own role. When a compound is placed in a magnetic field, the electrons around the protons also generate a magnetic field called *induced magnetic field*. The induced magnetic field may oppose or reinforce (support) the applied field. The field felt by the proton is then the resultant of the applied and induced fields.

When the induced field opposes the applied field, the effective field strength experienced by the proton decreases. Thus a stronger field must be applied for the excitation of protons to higher level. The proton is now shielded and absorbs more **upfield**.

When the induced field reinforced or supports the applied field, an enhanced field strength will be experienced by the proton. Such a proton is **deshielded** and absorbs more **downfield** (i.e., at lower magnetic field strength).

As a result of shielding and deshielding of protons, there is a shift in the position of the signal.

18.8 Equivalent and non-equivalent Protons

Protons in the same environment are called **Chemically equivalent protons.** In other words, protons in a molecule having the same environments absorb at the same magnetic fields strength, are called *equivalent protons. All equivalent protons give rise to one signal in the NMR spectrum. From the number of signals, we can tell how many different types of protons are there in a molecule.* Equivalent protons are indicated by the same letter, and non-equivalent protons by different letters.

Protons which have different environment absorb at different magnetic fields, are called **non-equivalent protons.**.

Magnetically equivalent protons are also chemically equivalent and vice-versa. We can judge whether the two (or more) protons are chemically equivalent or not, by the isomer number method.

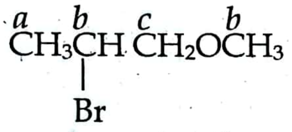
For example, 1-bromopropane, ($CH_3CH_2CH_2Br$) has three different sets of chemically equivalent protons. The three methyl protons are chemically equivalent because of rotation about the C – C bond. The two methylene protons on the middle carbon are chemically equivalent, and the two methylene protons on the carbon bonded to the bromine atom make up the third set of chemically equivalent protons.

Each set of chemically equivalent protons in a compound gives rise to a signal in the ^1H NMR spectrum of that compound. Because 1-bromopropane has three sets of chemically equivalent protons, it has three signals in its ^1H NMR spectrum.

2-Bromopropane has two sets of chemically equivalent protons and, therefore, it has two signals in its ^1H NMR spectrum; the six methyl protons in 2-Bromopropane are equivalent, so they give rise to only one signal. Ethyl methyl ether has three sets of chemically equivalent protons: the methyl protons on the carbon adjacent to the oxygen, the methylene (CH_2) protons on the carbon adjacent to the oxygen, and the methyl protons on the carbon that is one carbon removed from the oxygen.

$\overset{a}{C}H_3\overset{b}{C}H_2\overset{c}{C}H_2Br$

three signals



$\overset{a}{C}H_3\underset{Br}{\overset{b}{C}H}\,\overset{c}{C}H_2O\overset{b}{C}H_3$

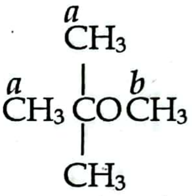
three signals

$\overset{a}{C}H_3\overset{c}{C}H_2O\overset{b}{C}H_3$

three signals

$\overset{a}{C}H_3O\overset{a}{C}H_3$

one signal



$\overset{a}{C}H_3\,\overset{\overset{a}{C}H_3}{\underset{CH_3}{C}}O\overset{b}{C}H_3$

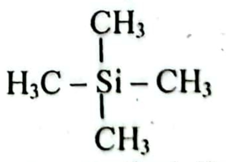
two signals

We can tell how many sets of chemically equivalent protons a compound has from the number of signals in its ^1H NMR spectrum.

18.9 The Chemical Shift

The shift in the positions of PMR signal, compared with a reference compound, as a result of shielding and deshielding by electrons is referred to as **chemical shift.** The shielding and deshielding effects cause the absorptions of protons to be shifted from the position at which bare proton to be shifted from the stripped of its electrons. Since these shifts result from the circulations of electrons in *chemical* bonds, they are called *chemical shifts.*

Chemical shifts are measured with reference to the absorption of protons of reference compounds. A reference is used because it is impractical to measure the actual value of the magnetic field at which absorptions occur. The reference compound most commonly used is tetramethylsilane (TMS).



$H_3C-\overset{CH_3}{\underset{CH_3}{Si}}-CH_3$

tetramethylsilane

A small amount of tetramethylsilane is added to the sample whose NMR spectrum is to be taken and the signal from the 12 equivalent protons of tetramethylsilane is used to establish the zero point on the delta scale.

Tetramethylsilane was chosen as a reference compound for several reasons as follows:

1. It is chemically inert.
2. Its resonance signal is very sharp due to twelve equivalent protons in it.
3. Its boiling point is very low so that it can be easily removed under study.
4. Its resonance position is to the high field side of various type of protons due to large diamagnetic shielding.
5. Most of the organic compounds for structural investigation are soluble in TMS.

With this standard substance, two scales are used for measuring chemical shift.

(a) **δ scale.** This sets the resonance of TMS arbitrarily at zero and counts lower field as positive.

In this δ scale a positive value of δ means down filed absorption by the sample. Absorption at lower field corresponds to a higher δ value.

(b) **τ scale (tau scale).** This scale sets the TMS resonance at 10. Thus the resonance are measured at lower than 10. Absorption at lower field corresponds to lower τ value. The δ scale and τ scale are shown below in Fig.18.4.

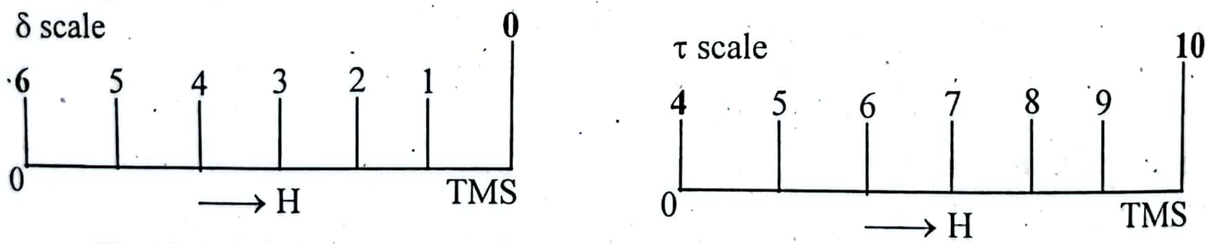


Fig.18.4. δ scale and τ scale for chemical shift.

Thus the relation between τ and δ is

$$\delta = 10 - \tau$$

It is to be noted that the substance having higher τ or lower δ values are said to be at up field indicating greater shielding effect while in the reverse case the substance is said to be at down field indicating de-shielding effect. Upfield and downfield cases are discussed below under the heading. The factors influencing chemical shifts.

Chemical shifts are measured in hertz (cycles per second), as if the frequency of the electromagnetic radiation were being varied. In actually it is the magnetic field that is changed. But since the values of frequency and the strength of the magnetic field are mathematically related, frequency units (hertz) are appropriate ones.

The chemical shift of a proton, when expressed in hertz, is proportional to the strength of the external magnetic field. Since spectrometers with different magnetic field strengths are commonly used, it is desirable to express chemical shifts in a form that is independent of the strength of the external field. This can be done easily by dividing the chemical shift by frequency of the spectrometer, with both numerator and denominator of the fraction expressed in frequency units (Hertz). Since chemical shifts are always very small (typically less than 500 Hz) compared with the total field strength (commonly the equivalent of 30, 60, and 100 *million* Hz), it is convenient to express these fractions in units of parts per million (ppm). This is the origin of delta scale for the expression of the chemical shifts relative to TMS.

$$\delta = \frac{(\text{Observed shift from TMS in Hz}) \times 10^6}{(\text{operating frequency of the instrument in Hertz})}$$

Most proton chemical shifts fall in the range from 0 to 10 ppm.

The ^1H NMR spectrum for 1-Bromo-2,2-dimethylpropane in Figure 18.5 shows that the chemical shift of the methyl protons is at 1.05 ppm and the chemical shift of the methylene protons is at 3.28 ppm. *Notice that low-frequency (upfield, shielded) signals have small δ (ppm) values, whereas high-frequency (downfield, deshielded) signals have large δ values.*

The advantage of the δ scale is that the chemical shift of a given nucleus is *independent of the operating frequency of the NMR spectrometer.* Thus, the chemical shift of the methyl protons of 1-Bromo-2,2-dimethylpropane is at 1.05 ppm in both a 60-MHz and a 360-MHz instrument. The following diagram will help you keep track of the terms associated with NMR spectroscopy:

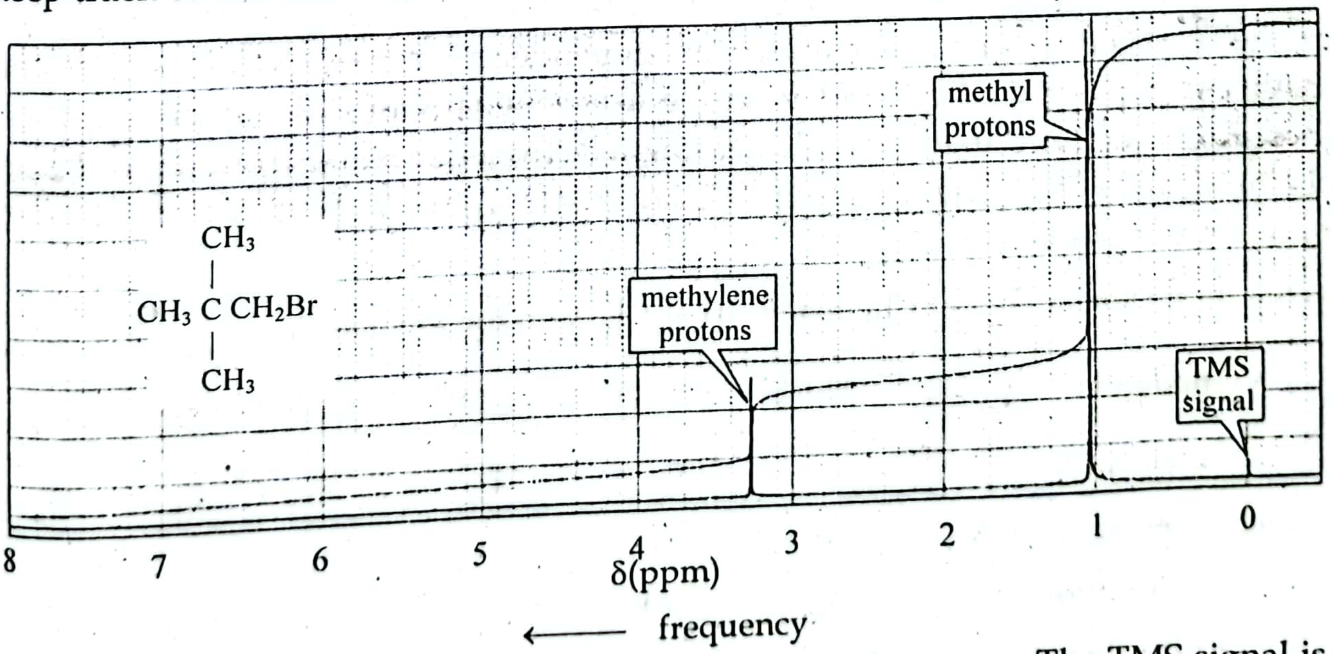


Fig.18.5. ^1H NMR spectrum of 1-Bromo-2,2-dimethylpropane. The TMS signal is a reference signal from which chemical shifts are measured; it defines the zero position on the scale.

Factors Affecting Chemical Shift

There are a number of factors which influence the chemical shift at which proton resonances occur. The major factors affecting chemical shifts are described below.

1. Inductive Effect

When a nucleus is placed in a uniform magnetic field, the electrons surrounding it circulate in such a manner as to produce a secondary field which reduces the influence of the external magnetic field on the nucleus. This shielding influence of the surrounding electrons may decrease if another electronegative atom is attached to the nucleus because the protective electron clouds are pulled away towards the neighbouring electronegative atom, causing it to come to resonance at a lower value of the external magnetic field. On the other hand, groups which donate electrons will tend to increase the electron density around the nucleus and hence a higher value of the external field will be required for resonance to occur since the nucleus is more shielded from the influence of the external magnetic field. The influence of **electronegativity** on the chemical shift can be explained as follows.

The trend of chemical shifts which is easiest to explain is that involving electronegative elements substituted on the same carbon to which the protons of interest are attached. The chemical shift simply increased as the electronegatvity of the attached element increases. The dependence of the chemical shifts of methyl groups in methyl halides on the electronegativities of halogens can be seen from the fact that with decreasing electronegativities from F to I, the chemical shifts of the methyl groups also decrease from 4.13 ppm in CH_3F to 1.98 ppm in CH_3I (table 18.1)

Table. 18.1. Dependence of Chemial Shift of CH_3X on the Element X

Compound CH_3X	CH_3F	CH_3OH	CH_3Cl	CH_3Br	CH_3I	CH_4
Element X	F	O	Cl	Br	I	H
Electronegativity of X	4.0	3.5	3.1	2.8	2.5	2.1
Chemical Shift δ	4.26	3.40	3.0	2.68	2.16	0.23

Multiple substituents have a stronger effect than a single substituent. The influence of the substituent drops off rapidly with distance, an electronegative element having little effect on protons which are more than three carbons distant.

Electronegative substituents attached to a carbon atom, because of their electron-withdrawing effects, reduce the valence electron density around the protons attached to that carbon. These electons, it will be recalled, shield the proton from the applied magnetic field. This effect, called local diamagnetic shielding. Electro-negative substituents on carbon reduce the local diamagnetic shielding in the vicinity of the attached protons because they reduce the electron density around those protons. Substituents which have this type of effect are said to deshield the proton. The greater the electronegativity of the substituents, the more it deshields protons and hence the greater is the chemical shift of those protons.

2. Hybridization Effects

The state of hybridization of the carbon atom to which a poton is attached significantly influences the chemical shift of the proton with increasing "s" character of the carbon, the bonding electrons will be drawn closer towards the carbon and away from the hydrogen, thus decreasing the electron desnity around the proton. This will result in the "*desheilding*" of the proton and it will therefore come to resonance at greater distances from the TMS signal. It has been found that change from sp^3 hybridization in ethane (25% "s" character) to sp hybridization in acetylene (50% "s" character) would cause a downfield shift of 5 – 8 ppm.

3. van der Waals Effects

If protons are forced into positions which are spatially very close to one another, van der Waals repulsive forces distort the electronic clouds which shield the protons. The reduced sphereical symmetry of the electron cloud around the protons give rise to a paramegnetic contribution to the shielding constants, thus causing deshielding or "downward" shift in the positions of the proton resonances.

4. Diamagnetic Anistropy

In electromagnetic terminology, an isotropic field is one of either uniform density or spherically symmetric distribution; an anisotropic field is not isotropic; that is, it is nonuniform.

(i) Single Bonds. The electronic clouds around protons bonded to carbon atoms do not have spherical symmetry, but are asymme-

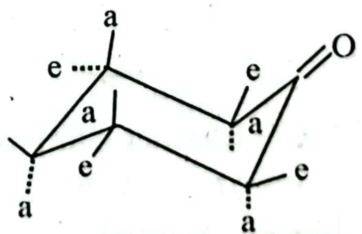


Fig. 18.6. In rigid cyclohexanone derivatives, axial protons are more shielded than equatorial protons.

trically distributed. The resulting secondary fields from protons are, therefore, "Anisotropic". A random tumbling of molecules will accordingly not result in their averaging to zero but will reinforce or diminish the applied field, depending on the orientation of the bonds. Thus in a rigid cyclohexane ring or in cyclohexanone (Fig.18.6), the axial protons are more shielded than the equatorial protons because of the anisotropy of the carbon framework so that they appear about 0.5 ppm further upfield than their equatorial counterparts.

(ii) Double Bonds. Anisotropic effects are even more marked in the case of double bonds such as C = C, C = O, and C = N which in contrast to single bonds, do not have axial symmetry. Thus in a double bond, the applied magnetic field causes an induced circulation of electrons which tends to oppose the applied magnetic field in the center of the double bond that reinforce at the ends. Figure 18.7 shows the induced circulation of electrons when the double bond is aligned at right angles to the applied field. In solution the tumbling molecules would, however, adopt any one of a large number of orientations, and the average of these various orientations would afford two shielding cones with their apexes meeting at the center of the double bond. Any protons which fall in the regions of these cones (+ zone) would be shielded whereas protons falling in the regions beyond the end of the double bonds (– zone) would experience a deshielding influence (Figure 18.8). Similar solutions would hold for C = S, C = N, and NO_2 groups.

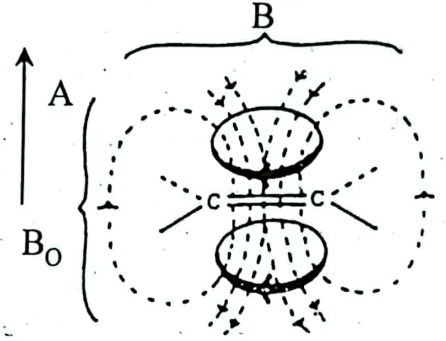


Fig. 18.7. Induced diamagnetic circulation of π electrons in a double bond. Nuclei lying in region A will be deshielded while those lying in region B will be shielded.

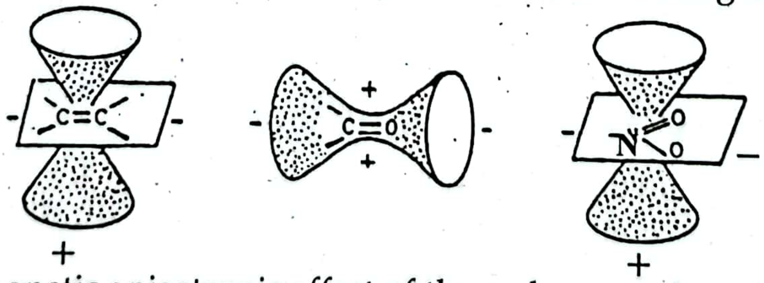
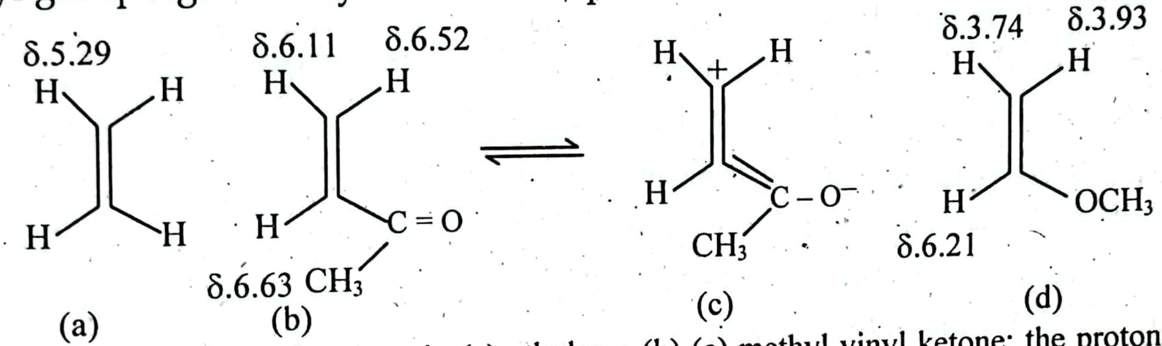


Fig.18.8. The magnetic anisotropic effect of the carbon – carbon double bond, the carbonyl group and the nitro group, and the resulting shielding (+) and desheilding (–) regions.

A striking example of such effects is provided by the aldehyde proton which lies in the desheilding zone of the carbonyl group and is therefore shifted considerably downfield. When substituents are attached to doubel bonds, they can signifcantly affect chemical shifts depending on their nature. In ethylene [Figure 18.8(a)] the olefinic protons resonate at δ 5.29. In methyl vinyl keone [Figure 18.8(b)] the proton α to the carbonyl group is strongly shielded region of the carbonyl group.

The olefinic proton β to the carbonyl group are deshielded on account of the electropositive character of the β – carbon because of the contribution of the resonance structure shown in figure 18.9 (c). When a methoxy substituent is present as in Figure 18.9 (d), the electron donation to the β – carbon atom by the methoxyl group significantly shields these protons.



(a) (b) (c) (d)

Fig. 18.9. Chemical shifts of protons in (a) ethylene; (b) (c) methyl vinyl ketone; the protons on the β to the carbonyl group are deshielded because of its electron-withdrawing effect (d) methyl vinyl ether; the opposing effect is now seen, the protons on the β carbon to the ethereal oxygen being strongly shielded due to its electron-donating effect.

Triple Bonds. Triple bonds such as those encountered in acetylenes or nitriles, have axial symmetry. As is shown in Fig. 18.10, the induced circulation of electrons in acetylenes or nitriles results in the generation of a secondary magnetic field which tends to oppose the applied field at the ends but reinforces it at a certain distance along the axis since acetylenic protons fall in the sheilding zone of the cone (Fig.18.10), they are shifted signficantly upfield and resonate at a value of δ 2.4, in contrast to olefinic which resonate at δ 4.6 to 6.0. If, however, anotherr proton is brought over the centre of the triple bond, it will be deshielded.

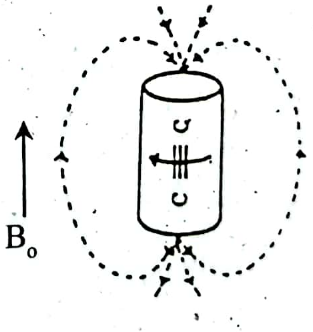


Fig.18.10. Diamagnetic circulation of π electrons about the axis of a triple bond.

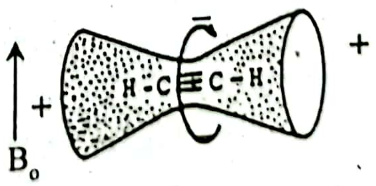


Fig. 18.11. The magnetic anisotropic effect of the triple bond.

18.10 Aromatic Rings

When benzene is placed in a magnetic field, the π electrons in the aromatic ring system are induced to circulate around the ring. This circulation is called a **ring current.** The moving electrons generate a magnetic field much like that in a loop of wire through which a current is induced to flow. The magnetic field covers a spatial volume large enough that it influences the shielding of the benzene hydrogens. Fig.18.12 illustrates this phenomenon by the diamagnetic anisotropy of the ring. An applied magnetic field is anisotropic in the vicinity of benzene molecule because the labile electrons in the ring interact with the applied field. This creates a nonhomogeneity in the immediate vicinity of the molecule. Thus, a proton attached to a benzene ring is influenced by the three magnetic fields. The strong magnetic field applied by the electromagnetic of the NMR spectrometer and two weaker fields, one due to the usual shielding by the valence electrons around the proton and the other due to the anisotropy generated by the ring-system π electrons anisotropic field. If a proton were placed in the center of the ring rather than on its periphery, it would be found to be shielded, centre of the ring rather than on its periphery, it would be found to be shielded, since the field lines there would have the opposite direction from those at the periphery.

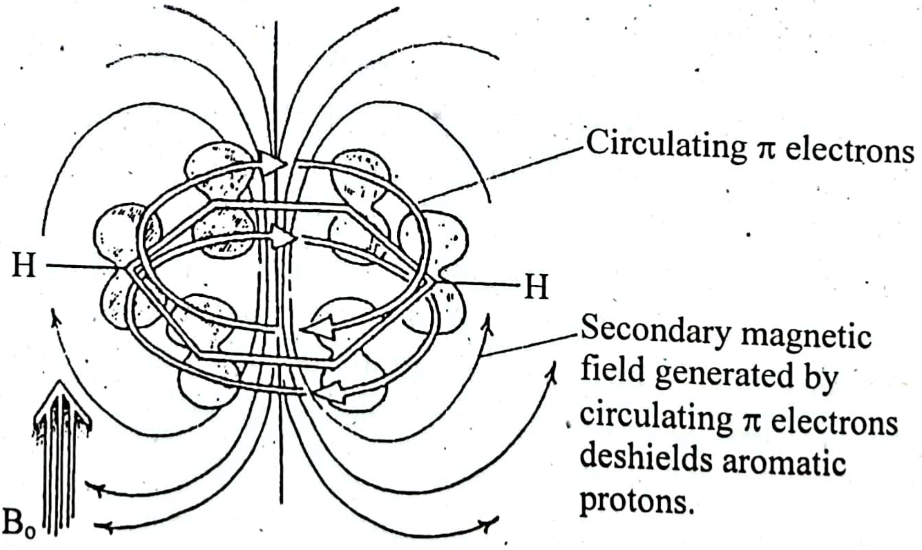


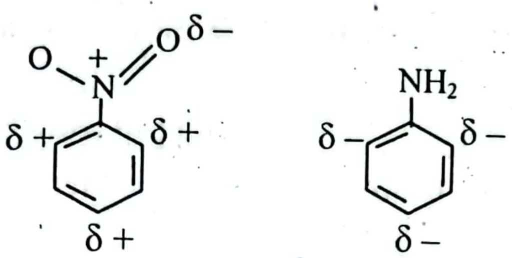
Fig. 18.12. Diamagnetic anisotropy in benzene

It should be noted that ring current effects are only discernible in planar conjugated cyclic molecules. In nonpolar molecules, e.g., cyclooctatetraene, which is tub-shaped, the delocalization of π-electrons is severely restricted, and the protons of cyclooctatraene therefore resonate in the normal olefinic region.

Table. 18.2. Chemical shifts of ortho, meta and para protons in monosubstitued benzenes

Substituent	δ, in ppm from benzene		
	Ortho	**Meta**	**Para**
NO_2	– 0.97	– 0.30	– 0.42
CHO	– 0.73	– 0.23	– 0.42
COOH	– 0.63	– 0.10	– 0.17
COOR	– 0.80	– 0.15	– 0.20
COR	– 0.6	– 0.3	– 0.30
$CONH_2$	– 0.5	– 0.2	– 0.2
$\overset{+}{N}H_3$	– 0.4	– 0.2	– 0.2
CN	– 0.3	– 0.3	– 0.30
NHCOR	– 0.4	0.2	0.3
I	– 0.3	0.2	0.1
	– 0.2	– 0.2	0.2
OCOR	– 0.2	0.1	0.2
SR	– 0.1	0.1	0.2
Cl	0.0	0.0	0.0
Br	0.0	0.0	0.0
CH_2Cl	0.0	0.0	0.0
CH_3	0.15	0.1	0.1
OCH_3	0.23	0.23	0.23
OH	0.37	0.37	0.37
$N(CH_3)_2$	0.5	0.2	0.5
NH_2	0.77	0.13	0.40

The effect of substituents on the chemical shifts of protons in aromatic rings can be described as follow. Strongly electron-withdrawing groups, such as nitro or aldehyde, result in significant deshielding of the aromatic protons, the *ortho* and *para* protons are more affected than the *meta* protons on account of the greater transmission of electropositive character of the *ortho* and *para* carbons by mesomerisation. Conversely, the presence of amino groups on benzene rings causes a sheilding of the *ortho* and *para* carbons because of the donation of electrons from nitrogen lone pair to these carbon atoms, resulting in an increase in the electron density at the positions.



(a) (b)

Fig. 18.13 (a) Nitrobenzene, showing the desheilding influence of the electron-withdrawing nitro group on the *ortho* and *para* protons. (b) Aniline, showing the sheilding influence of the electron-donating amino group on the *ortho* and *para* protons.

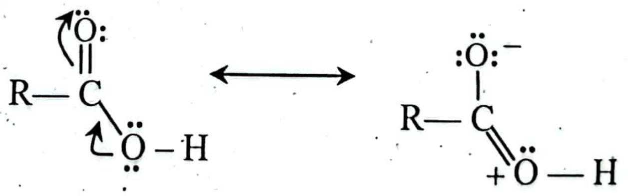
5. Solvent Effects

Substances dissolved in aromatic solvents generally give signals at higher fields than when dissolved in aliphatic solvents. These effects are attributed to the diamagnetic anisotropy of aromatic rings, and are more significant when intermolecular solute-solvent associations lead to complex formation. As a result of dipole - dipole or van der Waals interactions between the solute and solvent, some orientations of the solute molecules may be favoured than others, giving rise to shifts in the resonance frequencies of the protons of the solute molecules.

6. Acidic and Exchangeable protons: Hydrogen Bonding

Acidic Hydrogens

Some of the least shielded protons are those attached to carboxylic acids. These protons have their resonances at 10 to 2 ppm. Both resonance and the electronegativity effect of oxygen withdraw electrons from the acid proton.



18.11 Hydrogen Bonding

Hydrogen atom exibiting property of hydrogen bonding in a compound absorbs at a low field in comparison to one which does not. This is because a hydrogen atom involves in a hydrogen bonding is sharing its electron with two electronegative elements. As a result it is deshielded by itself and comes into resonance at low field. The downfield shift depends upon the strength of hydrogen bonding. Intermolecular and intramolecular hydrogen bonding can be easily distinguished as the latter does not show any shift in absorption due to change in concentration.

The resonance posiiton of most signals is little affected by temporature, although OH, NH and SH protons resonate at higher fields at higher temperature because the degree of hydrogen onding in carboxylic acid dimmers leads to very low-field absorption in δ in ppm than the corresponding intramolecular hydrogen bonding of enolised β-diketones.

18.12 Characteristic Values of Chemical Shifts

Approximate values of chemical shifts for different kinds of protons are shown in Table 18.4. An ^{1}H NMR spectrum can be divided into six regions. Rather than memorizing chemical shift values, if you remember the kinds of protons that are in each region, you will be able to tell what kinds of protons a molecule has from a quick look at its NMR spectrum.

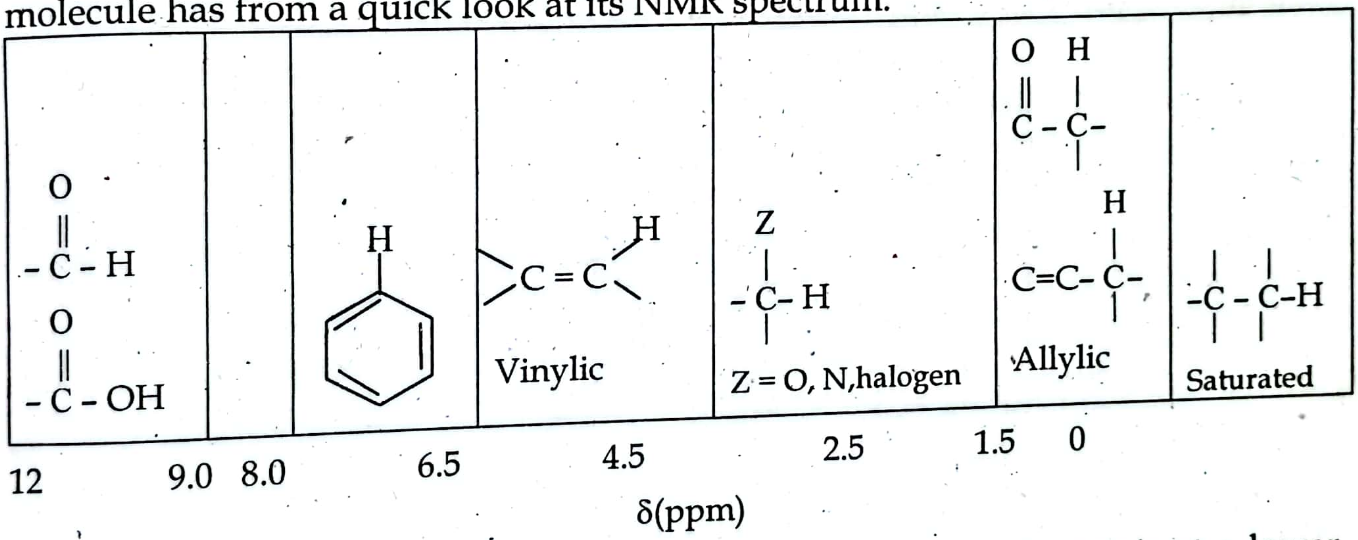
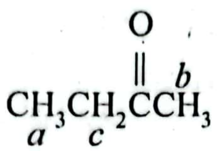


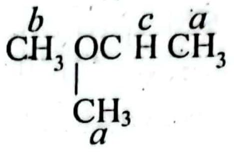
Table 18.3 shows that the chemical shift of methyl protons is at a lower frequency (0.9 ppm) than is the chemical shift of methylene protons (1.3 ppm) in a similar environment and that the chemical shift of methylene protons is at a lower frequency than is the chemical shift of a methine proton (1.4 ppm) in a similar environment and that the chemical shift of methylene proton is at a lower frequency than is the chemical shift of a methine proton (1.4 ppm) in a similar environment. (When an *sp* carbon is bonded to only one hydrogen, the hydrogen is called a **methine hydrogen.**) For example, the ^{1}H NMR spectrum of butanone shows three signals. The signal for the *a* protons of butanone is the signal at the lowest frequency because the protons are farthest from the electron-withdrawing carbonyl group. (In correlating an NMR spectrum with a structure, the set of protons responsible for the signal at the lowest frequency will be labeled *a*, the next set will be labeled *b*, the next set *c*, etc.) The band C protons are the same distance from the carbonyl group, but the signal for the *b* protons is at a lower

frequency because methyl protons appear at a lower frequency than do methylene protons in a similar environment.



$\overset{a}{\text{CH}_3}\overset{c}{\text{CH}_2}\overset{\text{O}}{\overset{\|}{\text{C}}}\overset{b}{\text{CH}_3}$

butanone

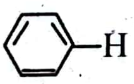
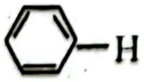


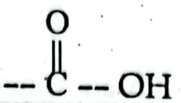
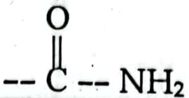
$\overset{b}{\text{CH}_3}\text{O}\underset{\underset{\text{CH}_3\ a}{|}}{\text{C}}\overset{c}{\text{H}}\overset{a}{\text{CH}_3}$

2-methoxypropane

The signal for the *a* protons of 2-methoxypropane is the signal at the lowest frequency in the ^{1}H NMR spectrum of this compound because these protons are farthest from the electron-withdrawing oxygen. The band *c* protons are the same distance from the oxygen, but the signal for the *b* protons appears at a lower frequency because, in a similar environment, methyl protons appear at a lower frequency than does a methine proton.

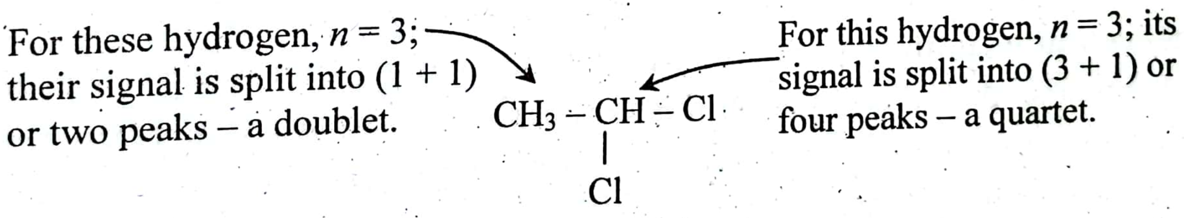
Table 18.3 Approximate values of chemical shift for ^{1}H NMR

Type of proton	Approximate chemical shift (ppm)	Type of proton	Approximate chemical shift (ppm)
$(\text{CH}_3)_4\text{Si}$	0		6.5 – 8
-- CH_3	0.9	$\overset{\text{O}}{\overset{\|}{\text{– C – H}}}$	9.0 – 10
$\overset{\text{O}}{\overset{\|}{\text{-- CH}_2\text{ --}}}$	1.3	$\text{I} - \underset{\|}{\overset{\|}{\text{C}}} - \text{H}$	2.5 – 4
$\text{-- }\underset{\|}{\text{C}} = \underset{\|}{\text{C}}\text{ -- CH}_3$	1.7	$\text{Br} - \underset{\|}{\overset{\|}{\text{C}}} - \text{H}$	2.5 – 4
$\text{-- }\overset{\text{O}}{\overset{\|}{\text{C}}}\text{ -- CH}_3$	2.1	$\text{Cl} - \underset{\|}{\overset{\|}{\text{C}}} - \text{H}$	3 – 4
	2.3	$\text{F} - \underset{\|}{\overset{\|}{\text{C}}} - \text{H}$	4 – 4.5
$\text{-- C} \equiv \text{C -- H}$	2.4	RNH_2	Variable, 1.5 – 4
R -- O -- CH_3	3.3	ROH	Variable, 2 – 5
$\text{R -- }\underset{\underset{\text{R}}{\|}}{\text{C}} = \text{CH}_2$	4.7	ArOH	Variable, 4 – 7

 $R-\underset{R}{C}=\underset{R}{C}-H$	5.3	 $-\overset{O}{\overset{\Vert}{C}}-OH$	Variable, 10 - 12
		 $-\overset{O}{\overset{\Vert}{C}}-NH_2$	Variable, 5 - 8

18.13 Signal Splitting and the (n + 1) Rule: Spin - Spin Coupling

Signal splitting is caused by magnetic fields of protons bonded to adjacent carbons. The splitting of a signal is described by the **n + 1 rule** where n is the number of *equivalent* protons bonded to *adjacent* carbons. By "equivalent protons" we mean that the protons bonded to an adjacent carbon are equivalent to each other, but not equivalent to the proton giving rise to the signal. Both signals in Fig. 18.4 (^1H NMR spectrum of 1-Bromo-2,2-dimethylpropane) are singlets because neither the carbon adjacent to the methyl groups nor that adjacent to the methylene group in 1-Bromo-2,2-dimethylpropane is bonded to any protons (n + 1 = 0 + 1 = 1). In contrast, in Fig.18.14 the carbon adjacent to the methyl group in 1,1-dichloroethane is bonded to one proton, so the signal for methyl protons is split into a doublet (n + 1 = 1 + 1 = 2). The carbon adjacent to the carbon bonded to the methine proton is bonded to the three equivalent protons, so the signal for the methine proton is split into a quartet (n + 1 = 3 + 1 = 4).

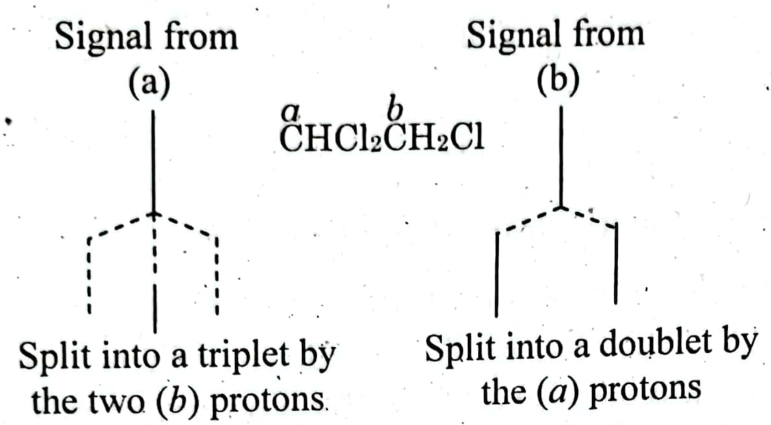

$CH_3-\underset{Cl}{CH}-Cl$

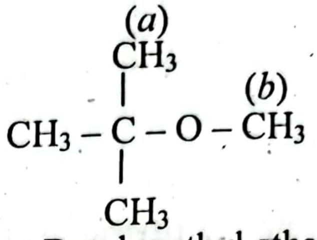
For these hydrogen, $n = 3$; their signal is split into (1 + 1) or two peaks – a doublet.

For this hydrogen, $n = 3$; its signal is split into (3 + 1) or four peaks – a quartet.

The number of peaks in a signal is called the **multiplicity** of the signal. Protons that split each other's signal are called **coupled protons.** Coupled protons are on adjacent carbons.

Signal splitting arises from phenomenon known as **spin-spin coupling.** Spin-spin coupling effects are transferred primarily through the bonding electrons and are *not usually observed if the coupled protons are separated by more than three σ bonds.* Thus we observe signal splitting from the protons of adjacent σ-bonded atoms as in 1,1,2-trichloromethane. However, we would not observe splitting of either signal of *tert*-butyl methyl ether because the protons labeled (b) are separated from those labeled (a) by more than three σ bonds. Both signals from *tert*-butyl methyl ether are singlets.





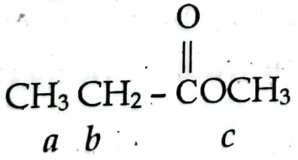
$$CH_3-\overset{\overset{(a)}{CH_3}}{\underset{CH_3}{\underset{|}{\overset{|}{C}}}}-O-\overset{(b)}{CH_3}$$

tert-Butyl methyl ether
(no signal splitting)

Signal splitting is not observed for protons that are chemically equivalent (homotopic) or enantiotopic. That is, signal splitting do not occur between protons that have exactly the same chemical shift, e.g., $CH_3 - CH_3$ (no signal splitting).

There is a subtle distinction between spin-spin coupling and signal splitting. Spin - spin coupling often occurs between sets of protons that have the same chemical shift. However, spin-spin coupling *leads to signal splitting only when sets of protons have different chemical shifts.*

Keep in mind that it is not the number of protons giving rise *to a signal that determines the multiplicity of the signal; rather, it is the number of protons bonded to the immediately adjacent carbons that determines the multiplicity.* For example, the signal for the α-protons in the compound ethyl acetate will be split into three peaks (α **triplet)** because the adjacent carbon is bonded to two hydrogens. The signal for the **b** protons will appear as a quartet because the adjacent carbon is bonded to three hydrogen and the signal for the **c** protons will be a singlet.



$$\underset{a}{CH_3}\,\underset{b}{CH_2}-\overset{\overset{O}{\|}}{C}O\underset{c}{CH_3}$$

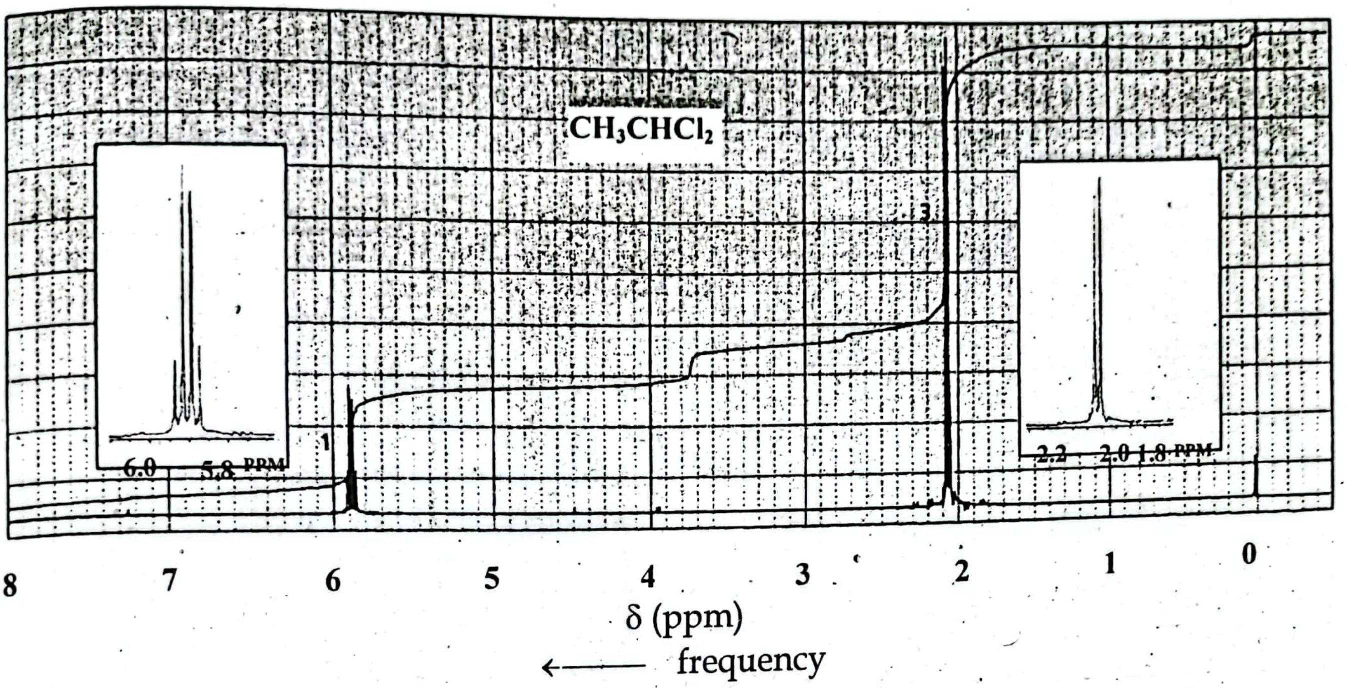


Fig.18.14. The NMR spectrum of 1,1-dichloroethane. The higher frequency signal is an example of a quartet; the lower-frequency signal is a doublet.

A signal for a proton is never split by *equivalent* protons. For example, the ^{1}H NMR spectrum of bromoethane shows one singlet, because the three methyl protons are chemically equivalent, and chemically equivalent protons do not split each other's signal. The four protons in 1,2-dichloroethane are also chemically equivalent, so its ^{1}H NMR spectrum also shows one singlet.

CH_3CH_2Br	$ClCH_2CH_2Cl$
Bromoethane	1,2-Dichloroethane

Q. How does the splitting of signals in the ^{1}H NMR spectrum of 1,3-Dibromopropane takes place?

Ans. There are two signals in the ^{1}H NMR spectrum of 1,3-Dibromopropane (Fig.18.15). The signal for the H_b protons is split into a triplet by the two hydrogens on the adjacent carbon. The H_a protons have two adjacent carbons that are bonded to protons. The protons on one adjacent carbon are equivalent to the protons on the other adjacent carbon. Because the two sets of protons are equivalent, the n + 1 rule is applied to both sets at the same time. In other words, n is equivalent to the sum of the equivalent protons on both carbons. So the signal for the H_a protons is split into a quintet (4 + 1= 5).

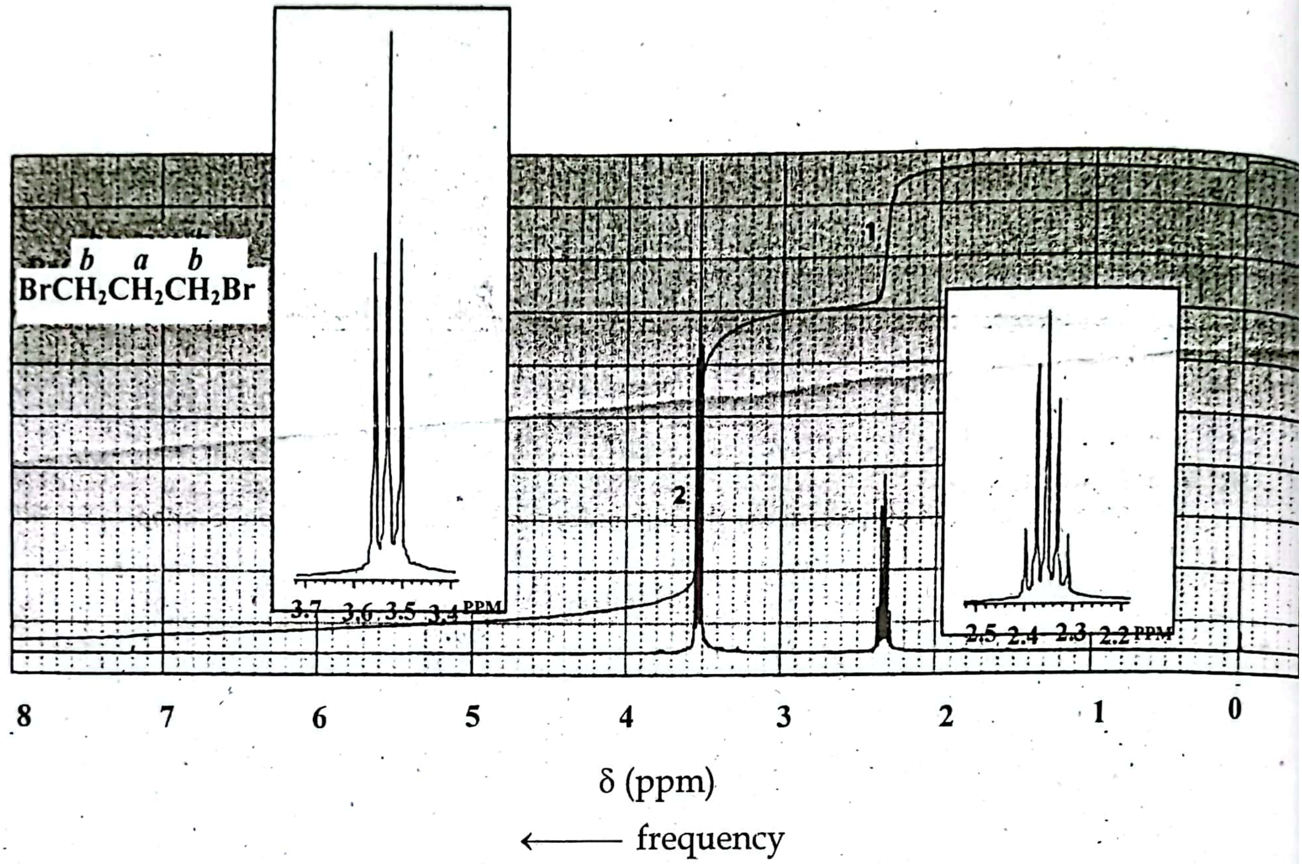


Fig. 18.15. ^1H NMR spectrum of 1,3-Dibromopropane.

Q. Describe the splitting of signals in ^1H NMR spectrum of isopropyl butanoate

Ans. The ^1H NMR spectrum of isopropyl butanoate shows five signals (Fig.(18.16). The signal for H_a protons is split into a triplet by the H_c protons. The signal for the H_b protons is split into a doublet by the H_e protons. The signal for the H_d protons is split into a triplet by the H_c protons, and the signal for the H_e proton is split into a septet by the H_b protons. The signal for the H_c protons is split by both the H_a and H_d protons. Because the H_a and H_d protons are not equivalent, the n + 1 rule has to be applied separately to each set. Thus the signal for H_c protons will be split into a quartet by the H_a protons, and each of these four peaks will be split into a triplet by the H_d protons: $(n_a + 1)(n_d + 1) = 4 \times 3 = 12$. As a result, the signal for the H_c protons is **multiplet** (a signal that is more complex than a triplet, quartet, quintet, etc.).

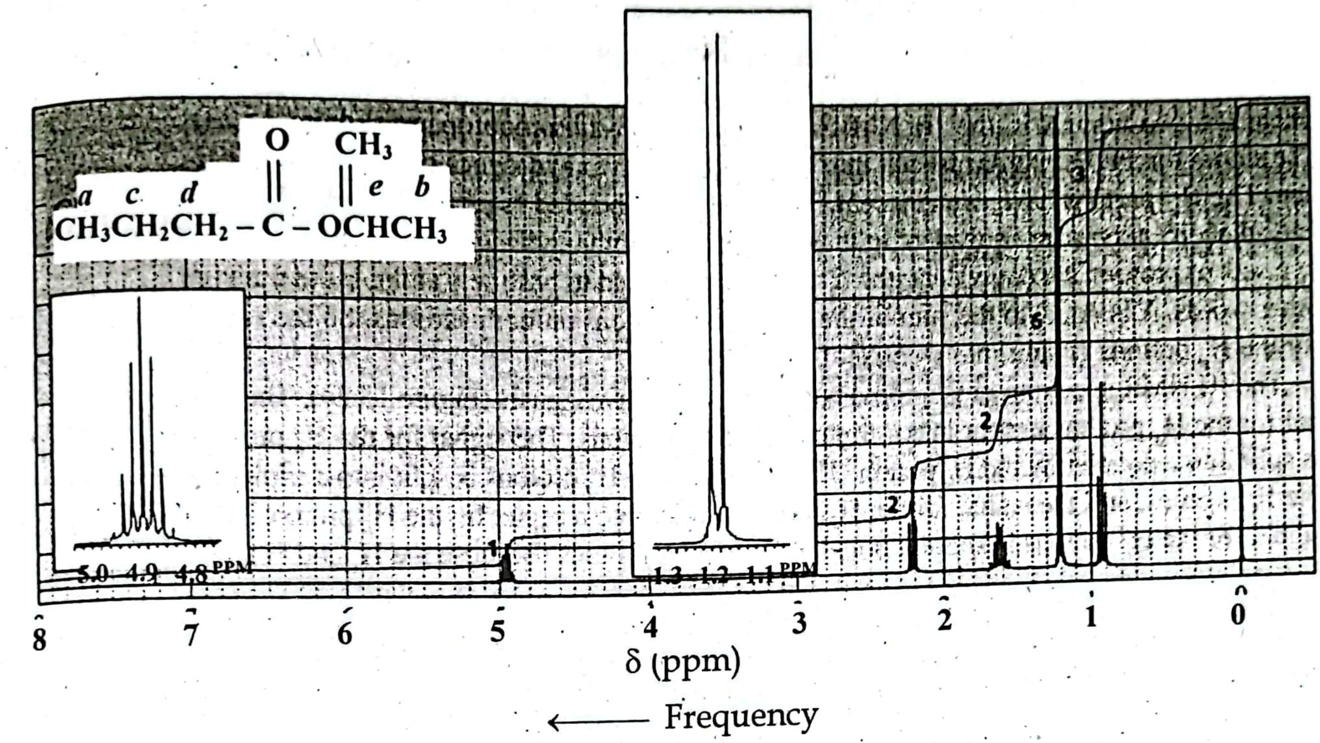
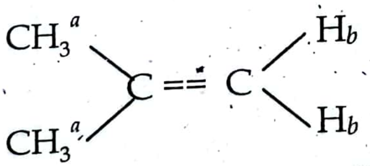


Fig.4.16. ¹H NMR spectrum of isopropyl butanoate.

Q. **Why is splitting observed in 2-Methylpropene but not in 1-chloro-2-2-dimethyl propane?**

Ans. In $(CH_3^{a})_3C-CH_2^{b}Cl$, H_a and H_b do not couple because they are not on adjacent C's; they are too far away from one another. In



although H_a and H_b are not adjacent C's, coupling is transmitted through the π-electrons.

18.14 COUPLING CONSTANTS

The distance, in hertz, between two adjacent peaks of a split NMR signal is called the **coupling constant,** denoted by J and is a quantitative measure of the shielding/deshielding influence of the magnetic moments of adjacent hydrogens. The magnitude of a coupling constant is expressed in hertz and for protons in ¹H NMR spectroscopy is generally in the range 0 – 18 Hz. The value of J depends only on fields caused by magnetic atoms within a molecule and is independent of the applied field strength. The coupling constant for H_a being split by H_b is denoted by J_{ab}. The signals of coupled protons (protons that split each other's signal) have the same coupling constant; in other words $J_{ab} = J_{ba}$ (Fig.18.17). Coupling constants are useful in analyzing complex NMR spectra because protons on adjacent carbons can be identified by their identical coupling constant.

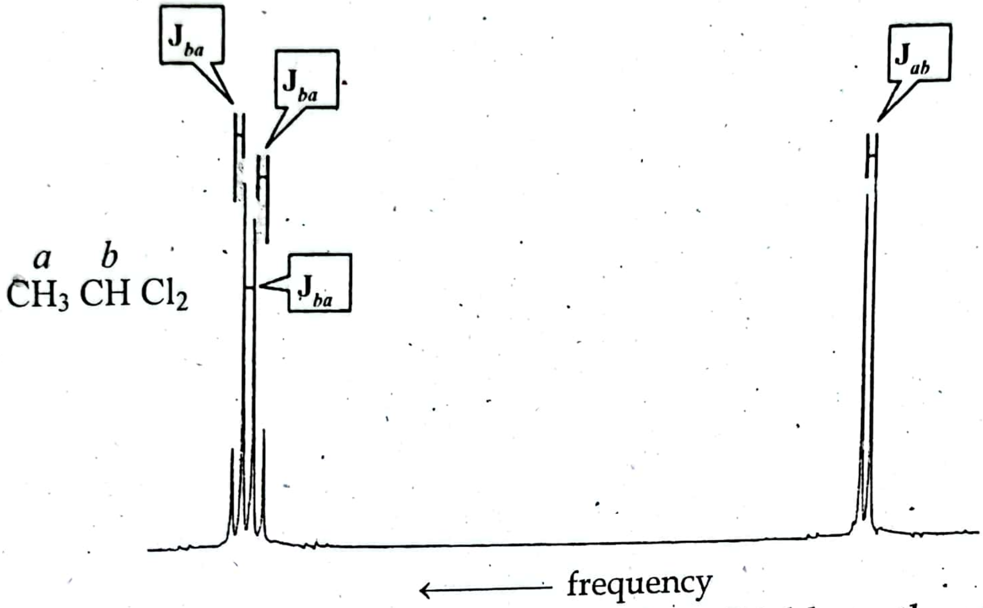


Fig.18.17. The H_a and H_b protons of 1,1-Dichloroethane are coupled protons, so their signals have the same coupling constant, $J_{ab} = J_{ba}$.

Factors Influencing the Coupling Constants

Coupling constants between coupled protons can vary with both in sign and in magnitude. Some of the more important factors influencing the coupling constants are (1) Dihedral angle between the C -- H proton (2) electronegativity of substituents (3) The C – C – H angle (4) Carbon – carbon bond length.

1. **Dihedral angle.** The most easily predictable influence on the coupling constant is that of the dihedral angle between the two vicinal C – H bonds. The C – C bond between the carbon atoms to which two coupled vicinal protons are attached, the angle which the protons make with one another is known as the **dihedral angle.** A Newman projection shown in Fig.18.18 illustrate this angle.

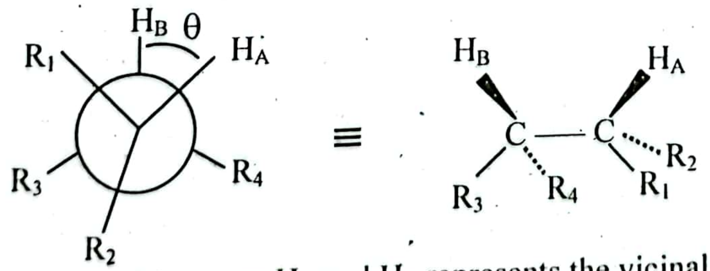


Fig.18.18. Angle θ between H_A and H_B represents the vicinal dihedral angle.

The near carbon atom is represented by a point to which H_A, R_1 and R_2 are attached while the rear carbon atom is represented by a circle to which H_B, R_3 and R_4 are attached. The relationship between the vicinal coupling constant (J) and the dihedral angle θ between the coupling protons is given approximately by the **Karplus equation.**

$J_{vic} = 10 \cos^2\theta$ when θ is between 0° and 90°

and $J_{vic} = 160 \cos^2\theta$ when θ is between 90° and 180°

The reliability of the relationship is not sufficiently high to justify accurate calculations because the calculations do not consider the factors like electronegativity of the substituents, bond angles and bond lengths. The correlation is useful only to the extent that the coupling constants are largest when the vicinal protons are *trans*-coplanar (i.e., θ = 180°), very small coupling constants are observed when the respective H – C – C planes are 90° to one another and large when the protons are *cis*-coplanar (i.e., θ = 0°). It is more convenient to express the relationships between the coupling constants and the dihedral angle in a graphic form, known as the **Karplus curve** (Fig.18.19).

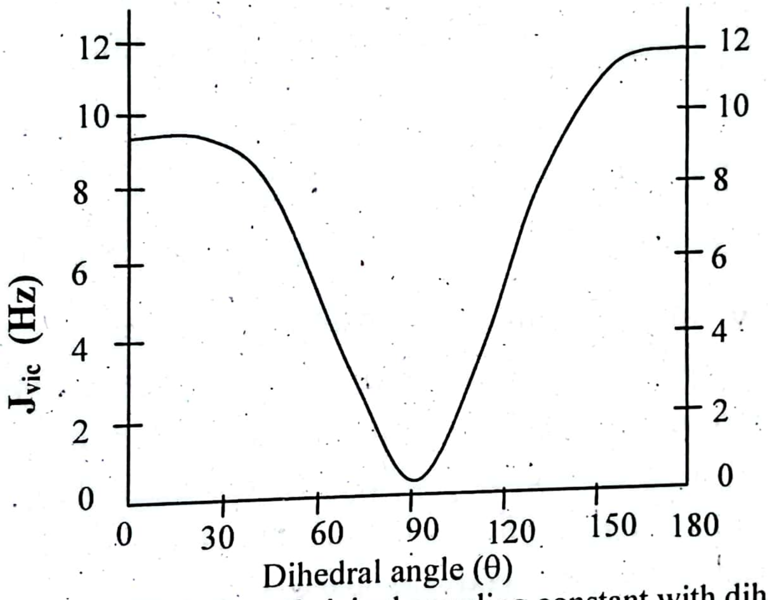
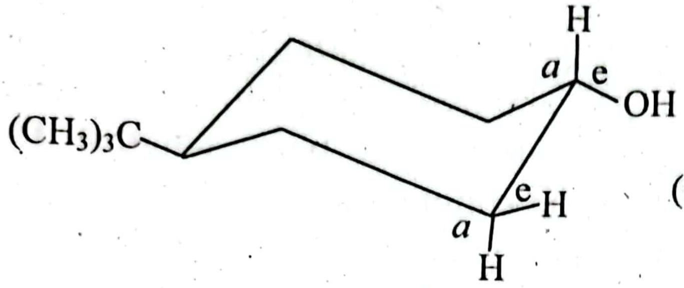
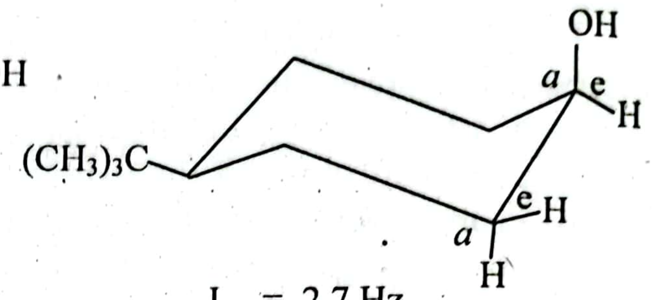


Fig.18.19. Variation of vicinal coupling constant with dihedral angle θ.

One of the most important applications of the Karplus equations is the chair conformation of the cyclohexane ring system where the predictions are in reasonable agreement with the observed values. Generally, the magnitude of the coupling constant for vicinal protons with diaxial orientation in cyclohexanes (where the dihedral angle is 180°) is 10 – 13 Hz, whereas the coupling constant associated with axial-equatorial or equatorial-equatorial interactions (where dihedral angle, θ is about 60°) is 2 – 5 Hz.

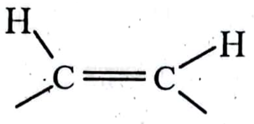




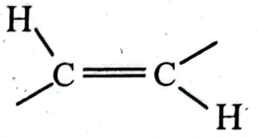
I_{aa} = 11.1 Hz
J_{ae} = 4.3 Hz

I_{ee} = 2.7 Hz
J_{ea} = 3.0 Hz

The Karplus relationship applied to the vicinal protons attached to the carbon-carbon double bond, leads to the prediction that the coupling constant for the *trans* protons ($\theta = 180^{o}$) is larger than that for the cis protons ($\theta = 0$).

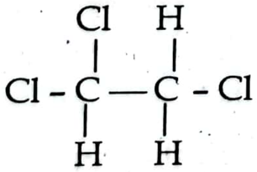


J_{cis} = 6 – 12Hz



J_{trans} = 12 – 18 Hz

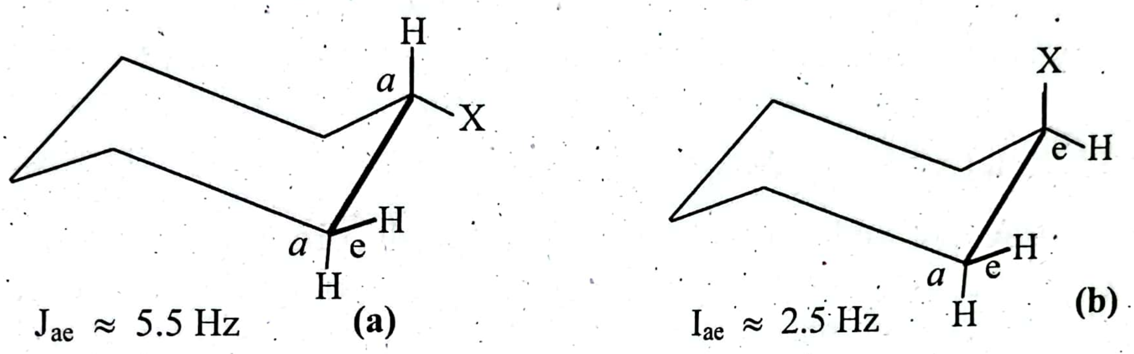
2. **Electronegativity of Substituents.** The magnitude of the coupling constant of vicinal protons may be altered by the electronegativity of the substituents in the neighbourhood in many ways. For a freely rotating substituted alkyl chain, such as – CH_2 – CH_2 – X, the vicinal proton coupling constant decreases with increasing electronegativity of the substituent, X. The effect is additive if more than one electronegative substituent is attached to the vicinal carbon atoms. For example, the J_{vic} for ethane is about 8Hz, whereas it is lowered to 6 – 7 Hz in haloethanes.



$\mathrm{Cl_2CH-CH_2Cl}$

J_{vic} = 6Hz

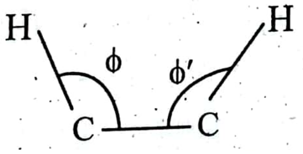
In cyclic systems, the effect of an electronegative substituent, X, on the vicinal coupling constant depends on the oreintation of X with respect to the coupled vicinal protons. The maximum effect of the substituent in reducing the vicinal coupling constant is observed when the substituent and a proton on the vicinal carbon are *trans*-coplanar. For example, in the chair confirmation of a cyclohexane system, J_{ae} is about 5.5 Hz when the substituent X is at equatorial position, but about 2.5 Hz when it is at axial position (where X = OH, Br, OAc, etc), despite the fact that the dihedral angle between the protons in both cases is about the same (~ 60^{o}). It appears that the electron-withdrawing effect of X in reducing the coupling constants is most effectively transmitted through the bonds when X and one of the coupling protons are *trans*-coplanar. This is very useful information as it allows the stereochemistry of the substituent X to be deduced from the magnitude of the axial-equatorial coupling constant. The electronegativity factor may thus cause large deviations from the values predicted by the Karplus equations.



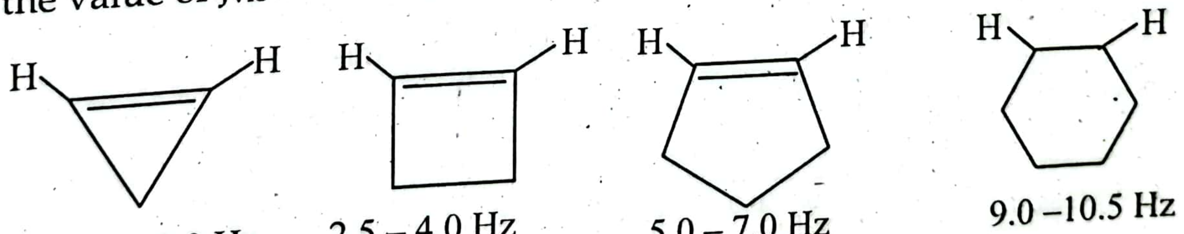
$J_{ae} \approx 5.5$ Hz **(a)** $I_{ae} \approx 2.5$ Hz **(b)**

Fig. 18.20 (a) The electronegative substituent X is not trans-coplanar with respect to H_a or H_e (b) Substitient X and H_a are trans-coplanar.

3. The C – C – H angle. Vicinal coupling constants depend markedly on the angles of ϕ and ϕ' between the C – H and C – C bonds as shown below:



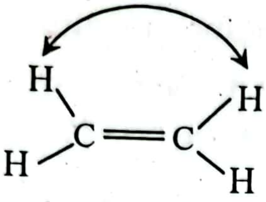
This effect is best illustrated in cyclic olefins in which the dihedral angle θ is zero and $\phi = \phi'$. In this case, as the angle ϕ decreases (with the increasing ring size), the value of J_{vic} increases, as shown below:



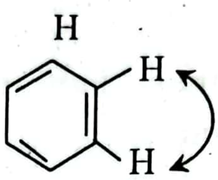
$J_{vic} = 0.5 – 2.0$ Hz 2.5 – 4.0 Hz 5.0 – 7.0 Hz 9.0 – 10.5 Hz

4. Carbon-carbon bond lengths / π Bond order

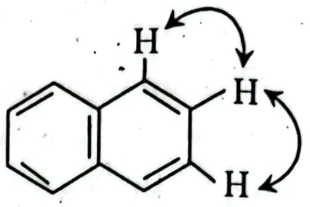
Vicinal coupling constants are very sensitive to small differences in the length of the C– C bond orders. It has been seen that for constant bond angles and nature of hybridization, the vicinal coupling constants decrease with increasing C – C bond lengths or decreasing π bond orders in unsaturated cyclic systems. Thus in ethylene, with a π bond order of 1, J = 11.5 Hz, while in benzene with a π bond order of 0.67, J = 8.0 Hz. In naphthalene, the 1,2-bond has a higher π bond order than the 2,3-bond, therefore, $J_{1,2}$ is greater than $J_{2,3}$



π-bond order 1.0
Coupling constant 11.5



0.67
8.0



1,2 2,3
0.72 0.60
8.1 6.4

18.15 Relative Peak Areas

The area under a NMR signal is directly proportional to the number of equivalent protons giving rise to that signal. By comparing the areas subtended by different signal, we can calculate the relative proportion of different types of protons. These areas can be electronically integrated by a NMR spectrum. Comparison of the areas provides the ratio among the various kinds of protons in the molecule. For example, consider the NMR spectrum of benzyl alcohol (Fig. 18.21). The area under the peaks are in the ratio 1 : 2: 5. indicating that three types of protons are in the ratio 1 : 2 : 5. This is actually so. Thus, there are one hydroxyl proton, two methylene protons and five ring protons. When no signal is present, it draws a horizontal line.

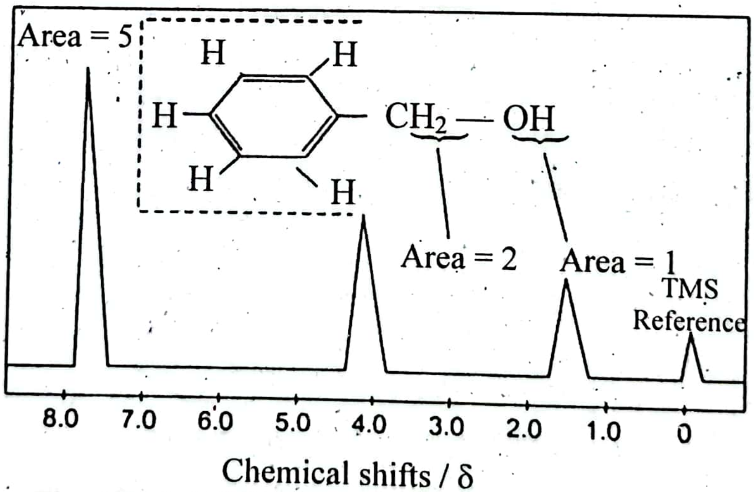


Fig. 18.21. NMR spectrum of benzyl alcohol

The peak areas of different signals are measured by an automatic electronic integrator. Also heights of peaks are proportional to area.

18.16 ^{13}C NMR Spectroscopy

The study of ^{13}C NMR spectroscopy shows some special features of spectra arising from carbon -13 nuclei. These spectra are often called carbon magnetic resonance (CMR) spectra or ^{13}C NMR spectra. Although ^{13}C occurs only 1.1% of naturally occurring carbon, the fact that ^{13}C can produce an NMR signal has profound importance for the analysis of organic compounds. The major isotope of carbon, on the other hand, carbon-12 (^{12}C), with natural abundance of about 99%, has no net magnetic spin and therefore cannot produce NMR signals. Moreover ^{13}C spectra are usually less complex and easier to interpret than proton (^{1}H) NMR spectra.

One aspect of ^{13}C NMR that greatly simplifies the interpretation process is that *each unique carbon atom in an ordinary organic molecule produces only one ^{13}C NMR peak.* There is no carbon – carbon coupling that causes splitting of signals into multiple peak. Recall that in ^{1}H NMR spectra, hydrogen nuclei that are near each other (within a few bonds) couple with each other and cause the signal for each hydrogen to become a multiple of peaks. This does not occur for adjacent carbons because only one carbon atom of every 100 carbon atoms is a carbon – 13 nucleus (1.1% natural abundance). Therefore, the probability of there being two carbon-13 atoms adjacent to each other in a molecule is only 1 in 10,000 (1.1% × 1.1%), essentially eliminating the possibility of two neighbouring carbon atoms splitting each other's signal into a multiplet of peaks.

Whereas carbon – carbon signal splitting does not occur in ^{13}C NMR spectra, hydrogen atoms bonded to the carbon can split ^{13}C NMR signals into multiple peaks. The multiplicity of the signal is determined by the N + 1 rule. However, it is possible to eliminate signal splitting by ^{1}H – ^{13}C coupling by choosing instrumental parameters for the NMR spectrometer that decouple the proton – carbon interactions. A ^{13}C NMR spectrum that has the proton interactions eliminated is said to be broadband (BB) proton decoupled, since proton – carbon interactions of all types are decoupled from the carbon signals. Thus, in a typical broadband decoupled ^{13}C NMR spectrum, each type of carbon atom produces only one peak. Most ^{13}C NMR spectra are obtained in this simplified decoupled mode.

18.17 Chemical Shifts in CMR Spectra

An important parameter derived from carbon – 13 spectra is the chemical shift. The chemical shifts appear over a range (0 to 220 ppm) much larger than that observed for protons (0 to 12 ppm). Because of the very large range of values, nearly every nonequivalent carbon atom in an organic molecule gives rise to a signal with a different chemical shift. Signals rarely overlap as they often do in proton NMR. Moreover, since the CMR spectra are generally recorded under proton-decoupling conditions, all the ^{13}C signals are singlets in an ordinary CMR spectrum. Like PMR spectroscopy the internal reference used in CMR spectroscopy is also trimethylsilane (TMS). Whereas the chemical shifts in PMR spectra are measured relative to the protons of TMS, the chemical shifts in CMR spectra are measured relative to the carbons of TMS, taken as zero. However, the addition of TMS in this case is often not necessary because the signals may be calibrated with reference to the solvent signal whose position relative to TMS is known. Most of the solvents used in NMR spectroscopy are deuterated. The deuterated carbons have longer relaxation time because of decreased dipole-dipole interaction. Their signals in the CMR spectra are, therefore, of low intensity. Deuterium (I = 1) has three spin states (–1, 0, +1) and when coupled to carbon, splits its signal into a 1 : 1 : 1 triplet. The multiplicity of the signal of a carbon atom having more than one attached deuterium atom, is given by (2nI + 1), where n is the number of deuterium atoms. Thus, the signal of a carbon atom is split into a quintet by two deuterium atoms and a septet by three deuterium atoms. ^{13}C chemical shifts of some common solvents are given in table 4.5.

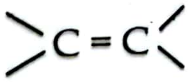
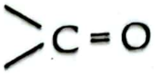
Table 18.4 ^{13}C Chemical Shifts of some Common Solvents

Solvent	**^{13}C Chemical Shift (ppm)**	**Deuteron – coupled multiplicity**
CCl_4	96.1	
CS_2	192.8	
$CDCl_3$	77.0	Triplet
CD_3OD	49.0	Septet
C_2D_5OD	15.8	Septet
	55.4	Quintet
$C_2D_5OC_2D_5$	13.4	Septet
	64.3	Quintet
CD_3CN	1.2	Septet
	117.8*	
CD_3COCD_3	29.8	Septet
	205.7*	
$(CD_3)_2SO$	39.7	Septet
C_6D_6	128.0	Triplet
Tetrahydrofuran – d_8	25.2	Quintet
	66.5	Quintet
1,4-Dioxane – d_8	67.4	Quintet
C_6D_{12}	26.3	Quintet

* Long – range multiplet not resolved.

Due to the wide span of ^{13}C signals, it is unlikely that two carbon atoms in a molecule have overlapping chemical shifts except that they are equivalent or enantiotopic. Usually, every individual carbon atom can be observed in a CMR spectrum. A proton - decoupled CMR spectrum will show that the number of different carbon atoms or different sets of equivalent carbon atoms present in a molecule. The multiplicity of a signal in an off - resonance decoupled CMR spectrum will indicate the number of hydrogen atoms attached to a particular carbon atom. The areas under the peaks in CMR spectra may not necessarily be proportional to the number of atoms responsible for these peaks. It is, therefore, not necessarily to determine the area ratios. The general trend of the chemical shift of ^{13}C is somewhat similar to that of the chemical shift of ^{1}H in similar groups. The going downfield from TMS, the general order is: alkanes, substituted alkanes, alkynes, alkenes, aromatics and carbonyl compounds. However, correlation of ^{13}C chemical shifts with the substituents electronegativity is not as good as that of ^{1}H chemical shifts. Furthermore, the given ^{13}C chemical shift values must not be taken too rigidly because of the use of the various reference compounds and solvents for their determination. For example, the absorption of carbonyl carbon of acetophenone appears at 2.4 ppm downfield in $CDCl_3$ than in CCl_4. The ^{13}C chemical shift regions for some representative types of carbon atoms, relative to TMS are given in table 4.6.

Table 18.5 **The Regions of ^{13}C chemical shifts of some representative types of carbon atoms**

Type of carbon atom	Chemical shift region (ppm)
RCH_3	0 – 35
R_2CH_2	15 – 40
R_3CH	25 – 50
RCH_2Br	20 – 40
RCH_2Cl	25 – 50
RCH_2NH_2	35 – 50
RCH_2OH	50 – 65
$-C\equiv C-$	65 – 90
	100 – 160
$-C\equiv N$	105 – 120
	110 – 175
	160 – 220

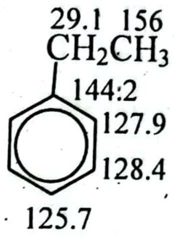
18.18 Factors Affecting ^{13}C Chemical Shifts

Chemical shifts in ^{13}C spectroscopy depend on various factors, as described below:

Effect of Hybridization. The range within which ^{13}C signals occur is greatly influenced by the state of hybridization of the observed nucleus. Thus the signals of the sp^3 - hybridized carbon atom appear most upfield (0 – 60 ppm), whereas the signals of sp^2-hybridized carbon atoms (100 – 160 ppm) appear about 100 ppm downfield from them, as shown in the case of 1 – octene.

δ(ppm) 114.0 139.0 34.1 29.1 29.3 32.1 22.9 14.1

$CH_2 = CH - CH_2 - CH_2 - CH_2 - CH_2 - CH_2 - CH_3$



The CMR spectrum of ethylbenzene shows two sets of ^{13}C signals about 100 ppm apart, as shown.

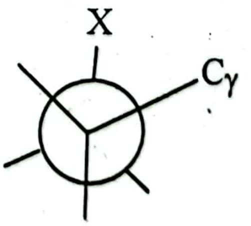
The carbon of alkenes and aromatic rings, both being sp^2 hybridized, appear in the same region; distinction between them can be made by their PMR spectra.

The sp-hybridized carbon atoms appear in the 65 – 90 ppm region, i.e., in between the regions of the sp^3- and sp^2-hybridized carbon atoms as shown in the case of 1-hexyne.

δ(ppm) 68.4 84.518.3 30.9 22.1 13.7

$CH \equiv C - CH_2 - CH_2 - CH_2 - CH_3$

Effect of Substituents. The effect of the substituents on the ^{13}C chemical shifts is different for the α–, β– and γ – carbon atoms of the substituted alkane (the carbon atom bearing the substituent is designated as α). The chemical shifts of even δ-carbon atom may be slightly affected by the substituents. The effect of the substituents on the α-carbon atom (commonly known as α – effect) is that its signal shifts downfield and this shift generally corresponds to the electronegativity of the substituents. The chemical shift of the β – carbon atoms (β – effect) also moves downfield. However, the chemical shift of the γ – carbon moves upfield. This upfield shift is considered to be due to the steric compression which pushes the electrons toward the carbon atom, resulting in its increased shielding, particularly when the substituents (X) and the γ – carbon atom are in gauche disposition as shown.



These effects become apparent on comparing the CMR spectral data of 1-chloropropane with that of n - pentane.

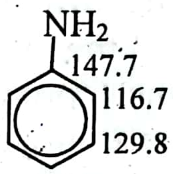
δ(ppm) 13.7 22.6 34.5 22.6 13.7

$CH_3 — CH_2 -- CH_2 -- CH_2 -- CH_3$

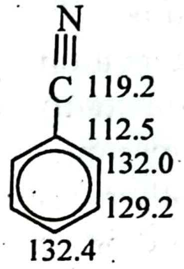
δ(ppm) 13.6 22.1 29.2 32.7 44.13

$CH_3 — CH_2 -- CH_2 -- CH_2 -- CH_2Cl$

Mesomeric Effect. Electron - donating groups, such as amino group, when attached to the benzene ring, donates its electron pair to the *ortho* and *para* carbon atoms by mesomeric effect and thus shields these carbon, resulting in the upfield shift of their ^{13}C signals. On the other hand, electron-withdrawing groups, such as nitrile group, deshield the *ortho* and *para* carbon atoms by the same effect, resulting in the downfield shift of their signals. This is shown by the chemical shift values in aniline and benzonitrile.

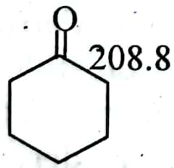


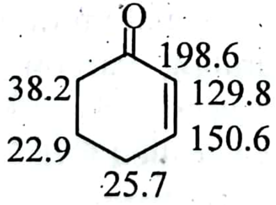
Aniline

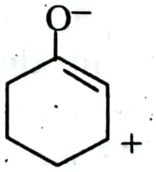


Benzonitrile

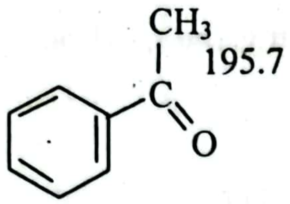
Similarly, in 2 - cyclohexanone, the carbonyl carbon experiences an upfield shift of its ^{13}C signal due to the presence of the conjugated double bond. This is because the partial positive charge on the carbonyl carbon atom is delocalized onto the β - carbon atom which then appears at downfield. The other carbon atoms (4, 5, and 6) of the ring, being sp^3 - hybridized appear at highly upfield.



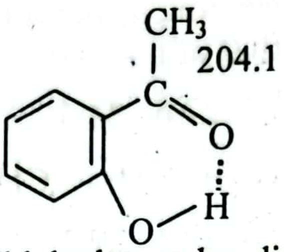




Effect of hydrogen - bonding. Carbonyl carbon atom which is involved in the formation of a hydrogen - bond through its oxygen atom, is deshielded and appears at downfield. Compare, for example, the chemical shift of the carbonyl carbon in acetophenone with that in *o* - hydroxyacetophenone.

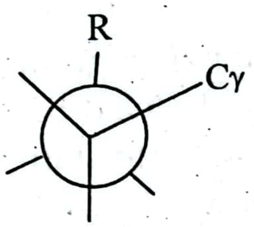


Without hydrogen bonding



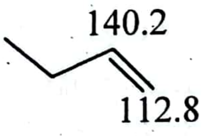
With hydrogen bonding

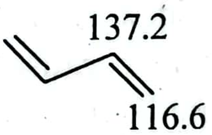
Steric and van der Waals Effects. Steric crowding of proton - bearing carbon atoms can result in their being shielded. Steric perturbation of C - H bonds results in the electrons moving away from the hydrogen atoms and towards the carbon atoms, thus resulting in the carbon atoms being shielded (and the protons deshielded). This effect is most pronounced when the proton-bearing carbon atoms and the substituents are in a γ-gauche disposition with respect to one another, resulting in steric crowding in the atoms as shown in Fig. Gauche hetero - atoms are generally more effective in producing upfield shifts than methyl or methylene groups.



Conjugation. Introduction of another double bond in conjugation with an existing double bonds results in a shielding effect as shown in the Fig.

Other factors. The ^{13}C chemical shifts are also influenced one way or the other way by anisotropic effect, nature of the solvent and pH of the solution.





18.19 Off - Resonance Decoupled Spectra

At times, more information than a predicted chemical shift is needed to assign an NMR peak to a specific carbon atom of a molecule. Fortunately, NMR spectrometers can differentiate among carbon atoms on the numbers of hydrogen atoms that are attached to each carbon. Several methods to accomplish this are available. An early method is called **Off - resonance decoupling**. In an off-resonance decoupled ^{13}C NMR spectrum each carbon signal is split into a multiplet of peeks, depending on how many hydrogens are attached to that carbon. An n + 1 rule applies, where n is the number of hydrogens on the carbon in question. Thus, a carbon with no hydrogens produce a singlet (n = 0), a carbon with one hydrogen produces a doublet (two peaks), a carbon with two hydrogens produces a triplet (three peaks), and a methyl group carbon produces a quartet (four peaks). Interpretation of off - resonance decoupled ^{13}C spectra, however, is often complicated by overlapping peaks from the multiplets.

18.20 Distortionless Enhancement Polarization Transfer (DEPT)

It is now possible to obtain ^{13}C NMR spectra that are much simpler to interpret with respect to carbon type. One such spectrum is called the **DEPT ^{13}C spectrum.** A DEPT spectrum actually consists of several spectra, with the final data presentation depictin one spectrum for each type of carbon atom. Thus CH, CH_2 and CH_3 carbons are each printed out on separate sub-spectra, together with a ^{13}C spectrum where all carbon types are shown. Such a spectrum for ipsenol, a monoterpene alcohol is shown in Fig. 4.22. The sub - spectrum *a* shows the ^{13}C signals for the CH_3 groups only. The signals for the CH_2 groups are shown in the sub-spectrum *b* while the signals for the CH groups are shown in the sub-spectrum c. The bottom - most spectrum (d) shows the signals for all carbons in the molecule. Note that a carbon which is not bonded to a hydrogen is not recorded in the DEPT experiment but of course a proton - decoupled CMR spectrum does show signals for all the carbons in the molecule.

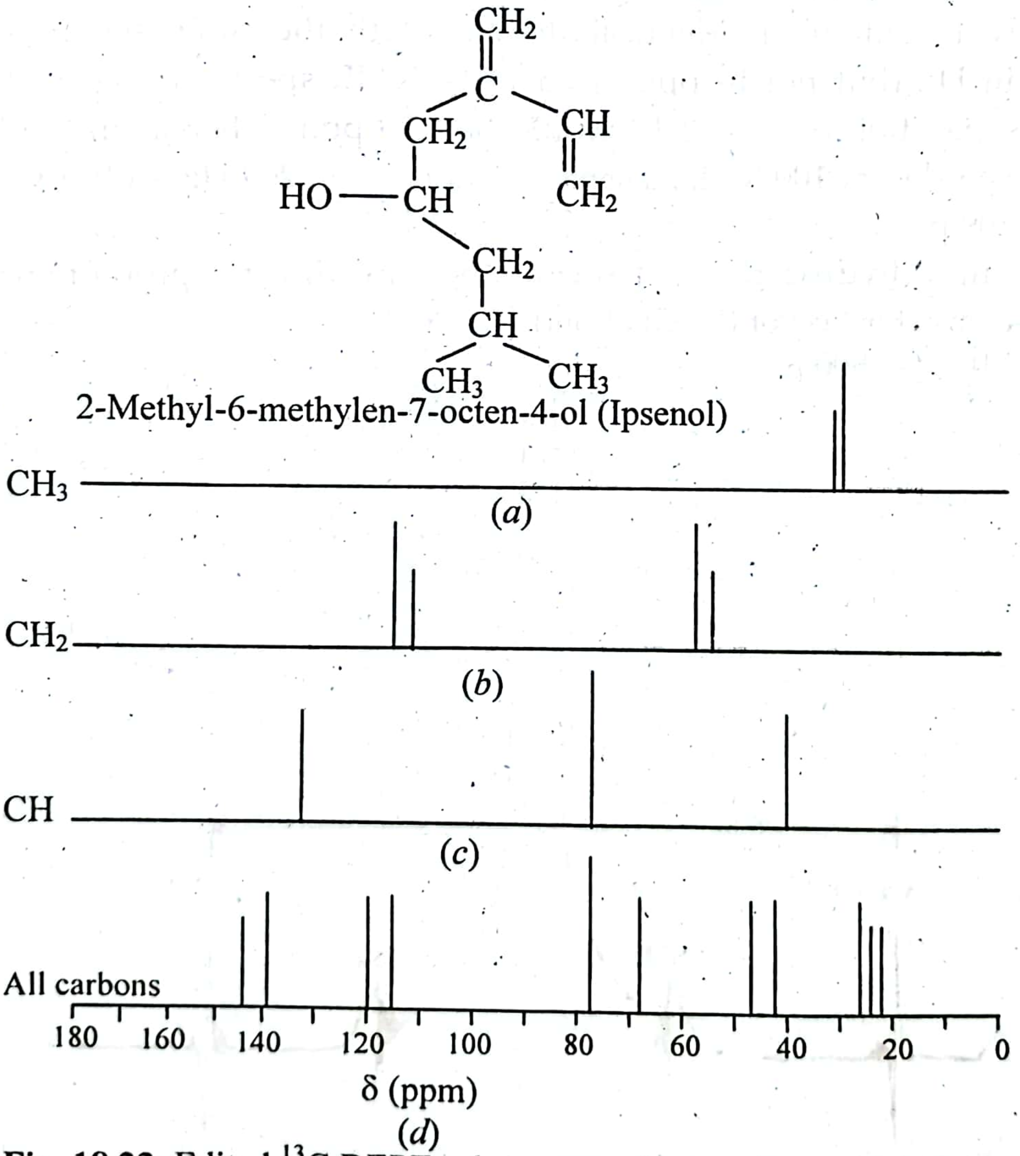


Fig. 18.23 Edited ^{13}C DEPT sub-spectra of ipsenol

The DEPT technique provides a more accurate method of distinguishing between CH, CH_2 and CH_3 group than the off – resonance decoupling technique, and is used in many laboratories as a routine. This is also accompanied by about four – fold enhancement in the signal intensity.

18.21 COUPLING IN ^{13}C – NMR SPECTROSCOPY

Carbon-Proton and Carbon-Carbon Coupling

1. **One – Bond Couplings:** $1J_{CH}$: Direct carbon – proton couplings, $1J_{CH}$, can be readily obtained by observing the ^{13}C satellite peaks in proton spectra. Since the abundance of ^{13}C is only 1%, the ^1H spectrum of pure $CHCl_3$ would contain a large singlet (Figure 4.23) due to $^{12}CHCl_3$, corresponding to 99% of molecules in the sample, and two "satellite" peaks (one on each side of the $^{12}CHCl_3$ peak with a separation from one another of 210 Hz) due to the $^{13}CHCl_3$ molecules. The ^{13}C spectrum will contain an identical doublet with the same separation when measured in Hz (but not in ppm; in a ^{13}C – NMR spectrum, recorded at 25.2 MHz, the separation of the peaks would be 8.33 ppm whereas in the ^1H-NMR spectrum recorded at 100 MHz, a separation of 209 Hz is observed, which is equal to 209 ppm).

In simple hydrocarbons $^1J_{CH}$ couplings are directly proportional to the extent of s-character (ρ) of the CH bond

$$^1J_{CH} = 500\,\rho$$

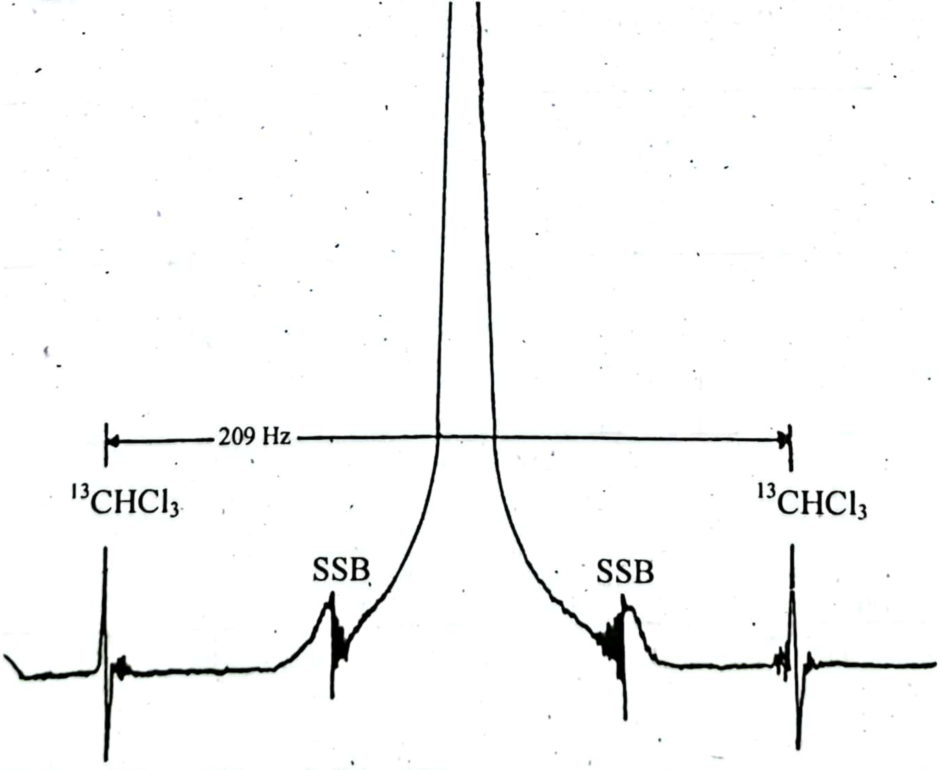


Fig.18.24 The 100 - MHz ^1H spectrum of pure $CHCl_3$, showing the spinning side bands (SSB) and ^{13}C satellites.

Thus in methane (sp^3 – hybridized carbons; s – character, 0.25) $^1J_{CH}$ = 125 Hz, in ethylene (sp^2 – hybridized carbons; s – character, 0.33) $^1J_{CH}$ = 167 Hz while in acetylene (sp –hybridized carbons ; s – character, 0.5) $^1J_{CH}$ = 250 Hz. The values of $^1J_{CH}$ couplings thus allow one to probe the extent of s – character in a given bond. For example, in cyclopropane $^1J_{CH}$ = 162 Hz, which is evidence of sp^2 hybridization in this molecule.

The magnitudes of $^1J_{CH}$ coupling vary considerably with the nature of the substituents, and the effects of substituents are largely additive. Thus $^1J_{CH}$ is 125 Hz for CH_4, 150 for CH_3Cl, 178 Hz for CH_2Cl_2, and 209 Hz for $CHCl_3$ (the additivity being less accurate for trisubstituted methanes).

The effect of electronegativity is even more marked when they are attached to sp^2 –hybridized carbons. Thus $^1J_{CH}$ in methyl cyanide is 136 Hz but in vinyl cyanide it is 177 Hz. The additivity of substituents effects on aliphatic carbons is given by the equation,

$$^1J_{CHz_1z_2z_3} = 125.0 + \sum_i Z_i$$

where z_1 , z_2 and z_3 are the substituents attached to a given carbon atom and Z_i is the increment for each group. The increment Z_i for various functional groups are given in table 4.7.

Table 4.7. Additivity rules for $^1J_{CH}$ coupling constants in aliphatic carbons

$$^1J_{CHz_1z_2z_3} = 125.0 + \sum_i Z_i$$

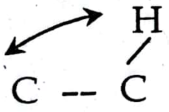
Substituents	**Increase Z_i^b**	**Substituent**	**Increase Z_i^b**
-- H	0.0		
-- CH_3	1.0	-- OH	18.0
-- $C(CH_3)_3$	-3.0	-- OCH_3	15.0
-- CH == CH_2	-3.0	-- O -- Phenyl	18.0
-- CH_2Cl	3.0	-- NH_2	8.0
-- CH_2Br	3.0	-- $NHCH_3$	7.0
-- CH_2I	7.0	-- $N(CH_3)_2$	6.0
-- $CHCl_2$	6.0	-- NO_2	22.0
-- CCl_3	9.0	-- SCH_3	13.0
-- C ≡ CH	7.0	-- $SOCH_3$	13.0

-- Phenyl	1.0	-- CHO	2.0
-- F	24.0	-- $COCH_3$	-1.0
-- Cl	27.0	-- COOH	5.5
-- Br	27.0	-- $COOCH_3$	5.0
-- I	26.0	-- CN	11.0

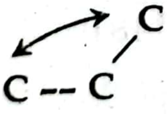
$^1J_{CC}$. One - bond carbon-carbon couplings, $^1J_{CC}$ vary on a large range, though they are generally smaller than $^1J_{CH}$ couplings due to the smaller magnetic moment of carbon in comparison to hydrogen. They are affected by the extent of s - character of the carbon atoms. In many compounds, it has been observed that there is a relationship between $^1J_{CC}$ and $^1J_{CH}$ which is in the case of a methyl group attached to a carbon atom may be expressed as.

$$^1J_{C-CH_3} = (0.27)\ ^1J_{C-H}$$

Two-Bond Couplings

$^2J_{CH}$ 

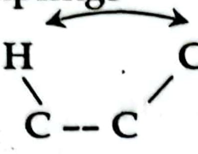
Coupling between carbon and hydrogen atoms separated by two bonds (e.g., C - C - H) are small, usually between - 6 and - 4 Hz in aliphatic systems. Introduction of electronegative substituents causes them to increase (i.e., their negative value decreases) and they can then occur between -5 and +2 Hz, the increase being maximum when the substituent is in the same plane as the C - C - H moiety. A useful feature of $^2J_{CH}$ couplings is that they are often 60 - 70% of the value of $^2J_{H-H}$ in a similar geometrical environment. Increasing the s - character of the C - C or C - H bonds causes an increase in the value of $^2J_{CH}$.

$^2J_{CH}$ 

Two - bond carbon-carbon couplings, $^2J_{CC}$ are usually less than 3Hz, particularly in saturated aliphatic systems. However, they can be larger if the central carbon atom is a carbonyl group, a cyano group or acetylenic.

Three Bond Couplings

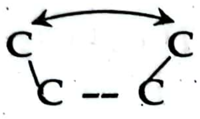
$^3J_{CC}$



Three – bond carbon-proton couplings, $^3J_{CH}$, depend on the dihedral angle θ between the planes containing the H – C – C and the C – C – C bonds, as in the case for vicinal proton couplings ($^3J_{HH}$).

The couplings are maximum when the dihedral angle is 180°, a little lower when it is 0°, and minimum when it is 90°. In olefins $^3J_{CH(cis)}$ is smaller than $^3J_{CH}(trans)$, a fact which may be used to ascertain the geometry of the olefins.

$^3J_{CC}$



Three – bond carbon couplings, $^3J_{CC}$, exhibit a dihedral angle dependence as do $^3J_{CH}$ couplings.

QUESTIONS

1. What type of information one can obtain from: (i) IR spectrum (ii) NMR spectrum.
2. What is meant by the term chemical shift of a particular proton in NMR spectroscopy? Draw the splitting patterns of protons in NMR spectrum of 1,1-dichloroethane.
3. How many NMR signals do you expect from each of the following compounds? Indicate also the splitting pattern of the various signals.
   (a) CH_3OCH_3 (b) $CH_3OCH_2CH_3$ (c) CH_3CH_2OH

Ans. (a) One signal (singlet); (b) three signals (singlet, quartet, triplet); Two signals (singlet, quartet.)

4. What is meant by integration of NMR signals? What integration tells us?
5. What is meant by "Shielding" in NMR spectroscopy?
6. How will you distinguish between the three dibromobenzenes by their NMR spectra?

Ans. *o*-Dibromobenzene will show two peaks; *m*-dibromobenzene will show three peaks; an *p*-dibromobenzene will show only one peak.