^{1}H-NMR Spectroscopy

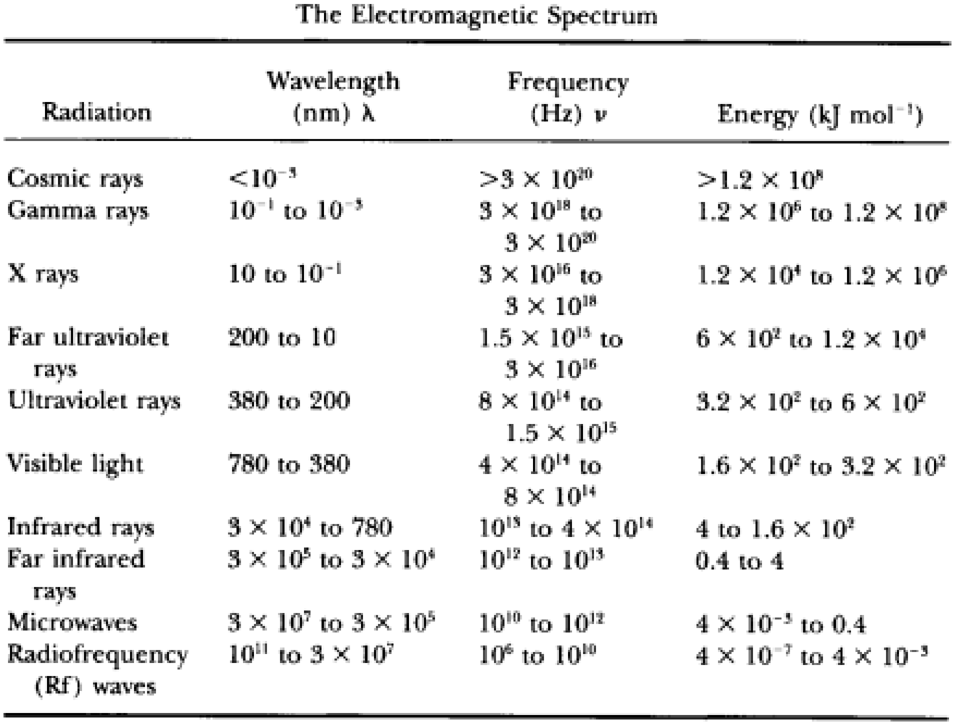
Nuclear magnetic resonance (NMR) spectroscopy is the study of molecules by recording the interaction of radiofrequency (Rf) electromagnetic radiation with the nuclei of molecules placed in a strong magnetic field. Zeeman first observed the strange behavior of certain nuclei subjected to a strong magnetic field at the end of the nineteenth century, but practical use of the so-called "Zeeman effect" was made only in the 1950s when NMR spectrometers became commercially available.

Like all other spectroscopic techniques, NMR spectroscopy involves the interaction of the material being examined with electromagnetic radiation. The simplest example of electromagnetic radiation is a ray of light, which occurs in the visible region of the electromagnetic spectrum and has a wavelength of 380 nm to 780 nm. Each ray of light can be thought of as a sine wave. However, this wave can actually be considered to be made up of two mutually perpendicular waves that are exactly in phase with each other; i.e., they both pass through their maxima and minima at exactly the same point of time. One of these two perpendicular waves represents an oscillatory electric field (E) in one plane, while the second wave, oscillating in a plane perpendicular to the first wave, represents an oscillating magnetic field, B.

Cosmic rays, which have a very high frequency (and a short wavelength), fall at the highest-energy end of the known electromagnetic spectrum and involve frequencies greater than $3x10^{20}$ Hz. Radiofrequency (Rf) radiation, which is the type of radiation that concerns us in NMR spectroscopy, occurs at the other (lowest-energy) end of the electromagnetic spectrum and involves energies of the order of 100 MHz (1 MHz = 10^6 Hz). Gamma rays, X rays, ultraviolet rays, visible light, infrared rays, and microwaves fall between these two extremes. The various types of radiation and the corresponding ranges of wavelength, frequency, and energy are presented in Table.

Electromagnetic radiation also exhibits behavior characteristic of particles, in addition to its wavelike character. Each quantum of radiation is called a photon, and each photon, exhibits a discrete amount of energy, which is directly proportional to the frequency of the electromagnetic radiation. The strength of a chemical bond is typically around 400 kJ $mo1^{-1}$, so that only radiation above the visible region will be capable of breaking bonds. But infrared rays, microwaves, and radio-frequency radiation will not be able to do so.

Let us now consider how electromagnetic radiation can interact with a particle of matter. Quantum mechanics (the field of physics dealing with energy at the atomic level) stipulates that in order for a particle to absorb a photon of electromagnetic radiation, the particle must first exhibit a uniform periodic motion with a frequency that exactly matches the frequency of the absorbed radiation. When these two frequencies exactly match, the electromagnetic fields can "constructively" interfere with the oscillations of the particle, and the system is then said to be "in resonance" and absorption of Rf energy can take place. Nuclear magnetic resonance involves the immersion of nuclei in a magnetic field, and then matching the frequency at which they are precessing with electromagnetic radiation of exactly the same frequency so that energy absorption can occur.



The Electromagnetic Spectrum

Radiation	Wavelength (nm) λ	Frequency (Hz) ν	Energy (kJ mol^{-1})
Cosmic rays	$<10^{-3}$	$>3 \times 10^{20}$	$>1.2 \times 10^{8}$
Gamma rays	10^{-1} to 10^{-3}	3×10^{18} to 3×10^{20}	1.2×10^{6} to 1.2×10^{8}
X rays	10 to 10^{-1}	3×10^{16} to 3×10^{18}	1.2×10^{4} to 1.2×10^{6}
Far ultraviolet rays	200 to 10	1.5×10^{15} to 3×10^{16}	6×10^{2} to 1.2×10^{4}
Ultraviolet rays	380 to 200	8×10^{14} to 1.5×10^{15}	3.2×10^{2} to 6×10^{2}
Visible light	780 to 380	4×10^{14} to 8×10^{14}	1.6×10^{2} to 3.2×10^{2}
Infrared rays	3×10^{4} to 780	10^{13} to 4×10^{14}	4 to 1.6×10^{2}
Far infrared rays	3×10^{5} to 3×10^{4}	10^{12} to 10^{13}	0.4 to 4
Microwaves	3×10^{7} to 3×10^{5}	10^{10} to 10^{12}	4×10^{-3} to 0.4
Radiofrequency (Rf) waves	10^{11} to 3×10^{7}	10^{6} to 10^{10}	4×10^{-7} to 4×10^{-3}

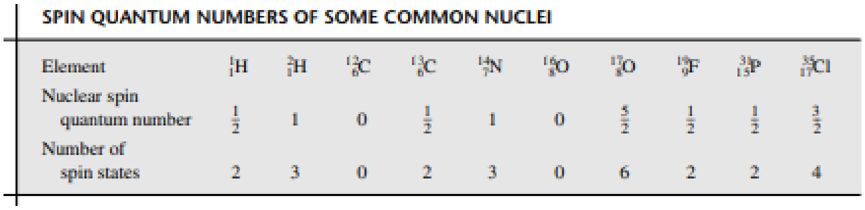
A. Nuclear Spin States:

Many atomic nuclei have a property called spin: the nuclei behave as if they were spinning. In fact, any atomic nucleus that possesses either odd mass, odd atomic number, or both has a quantized spin angular momentum and a magnetic moment. The more common nuclei that possess spin include $^{1}_{1}H$, $^{2}_{1}H$, $^{13}_{6}C$, $^{14}_{7}N$, $^{17}_{8}O$, and $^{19}_{9}F$. Notice that the nuclei of the ordinary (most abundant) isotopes of carbon and oxygen, $^{12}_{6}C$ and $^{16}_{8}O$, are not included among those with the spin property. However, the nucleus of the ordinary hydrogen atom, the proton, does have spin. For each nucleus with spin, the number of allowed spin states it may adopt is quantized and is determined by its nuclear spin quantum number I. For each nucleus, the number I is a physical constant, and there are 2I+1 allowed spin states with integral differences ranging from +I to −I. The individual spin states fit into the sequence

+I, (I-1), (I-2), ………., (-I+2), (-I+1), -I

For instance, a proton (hydrogen nucleus) has the spin quantum number **I** = $\frac{1}{2}$ and has two allowed spin states [2($\frac{1}{2}$) + 1 = 2] for its nucleus: − $\frac{1}{2}$ and + $\frac{1}{2}$. For the chlorine nucleus, **I** = $\frac{3}{2}$ and there are four allowed spin states [2($\frac{3}{2}$) + 1 = 4]: - $\frac{3}{2}$, - $\frac{1}{2}$, + $\frac{1}{2}$, and + $\frac{3}{2}$. Following table gives the spin quantum numbers of several nuclei.

In the absence of an applied magnetic field, all the spin states of a given nucleus are of equivalent energy (degenerate), and in a collection of atoms, all of the spin states should be almost equally populated, with the same number of atoms having each of the allowed spins.



SPIN QUANTUM NUMBERS OF SOME COMMON NUCLEI

Element	$^{1}_{1}H$	$^{2}_{1}H$	$^{12}_{6}C$	$^{13}_{6}C$	$^{14}_{7}N$	$^{16}_{8}O$	$^{17}_{8}O$	$^{19}_{9}F$	$^{31}_{15}P$	$^{35}_{17}Cl$
Nuclear spin quantum number	$\frac{1}{2}$	1	0	$\frac{1}{2}$	1	0	$\frac{5}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{3}{2}$
Number of spin states	2	3	0	2	3	0	6	2	2	4

B. NUCLEAR MAGNETIC MOMENTS

Spin states are not of equivalent energy in an applied magnetic field because the nucleus is a charged particle, and any moving charge generates a magnetic field of its own. Thus, the nucleus has a magnetic moment μ generated by its charge and spin. A hydrogen nucleus may have a clockwise (+ $\frac{1}{2}$) or counterclockwise (− $\frac{1}{2}$) spin, and the nuclear magnetic moments (μ) in the two cases are pointed in opposite directions. **In an applied magnetic field, all protons have their magnetic moments either aligned with the field or opposed to it**. Following figure illustrates these two situations.

Hydrogen nuclei can adopt only one or the other of these orientations with respect to the applied field. The spin state + $\frac{1}{2}$ is of lower energy since it is aligned with the field, while the spin state – $\frac{1}{2}$ is of higher energy since it is opposed to the applied field. This should be intuitively obvious to anyone who thinks a little about the two situations depicted in next figure, involving magnets. The aligned configuration of magnets is stable (low energy). However, where the magnets are opposed (not aligned), the center magnet is repelled out of its current (high-energy) orientation. If the central magnet were placed on a pivot, it would spontaneously spin around the pivot into alignment (low energy). Hence, as an external magnetic field is applied, the degenerate spin states split into two states of unequal energy, as shown in figure. In the case of a chlorine nucleus, there are four energy levels, as shown in figure. The + $\frac{3}{2}$ and – $\frac{3}{2}$ spin states are aligned with the applied field and opposed to the applied field, respectively. The + $\frac{1}{2}$ and – $\frac{1}{2}$ spin states have intermediate orientations, as indicated by the vector diagram on the right in Figure.

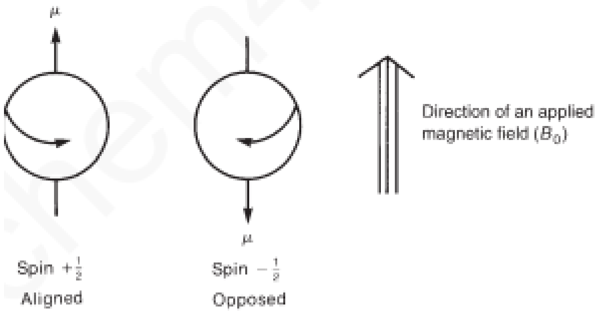


Fig. Two allowed spin states for a proton

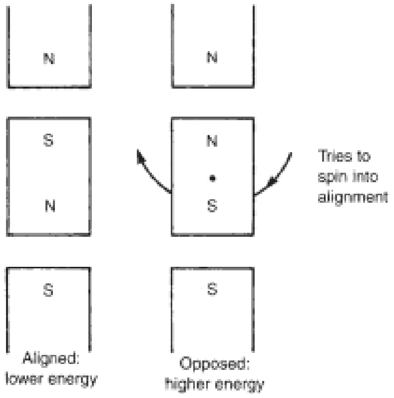


Fig. Aligned and opposed arrangement of bar magnets

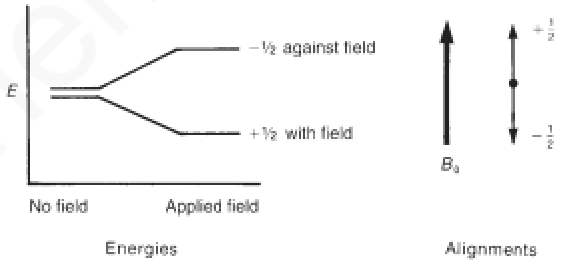


Fig. The spin states of a proton in the absence and in the presence of an applied magnetic field.

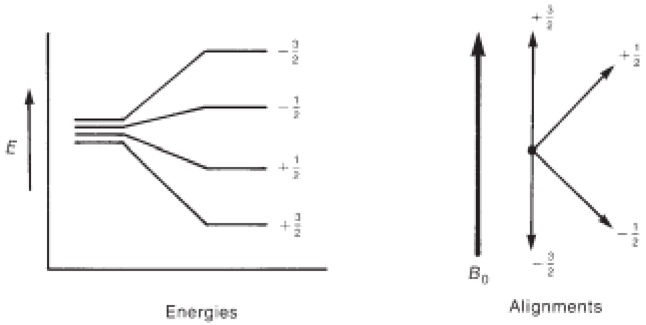


Fig. The spin states of a chlorine atom both in the presence and in the absence of an applied magnetic field.

C. ABSORPTION OF ENERGY:

The nuclear magnetic resonance phenomenon occurs when nuclei aligned with an applied field are induced to absorb energy and change their spin orientation with respect to the applied field. Figure 5 illustrates this process for a hydrogen nucleus. The energy absorption is a quantized process, and the energy absorbed must equal the energy difference between the two states involved.

$$E_{\text{absorbed}} = (E_{-\frac{1}{2}\text{state}} - E_{+\frac{1}{2}\text{state}}) = hv \qquad \text{Equation 1}$$

In practice, this energy difference is a function of the strength of the applied magnetic field B_0, as illustrate in figure,

FIGURE 3.5 The NMR absorption process for a proton

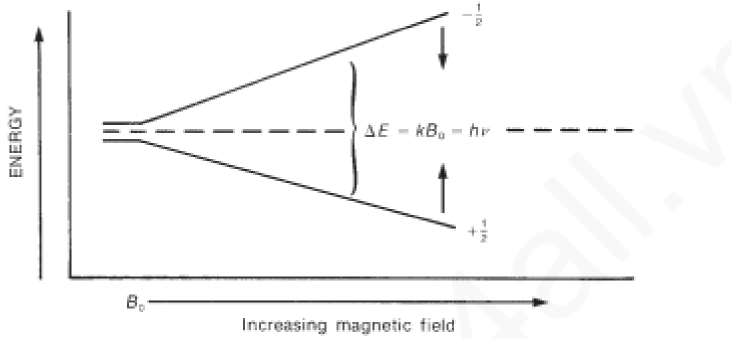


Fig. The spin state energy separation as a function of the strength of the applied magnetic field B_0

The stronger the applied magnetic field, the greater the energy difference between the possible spin states:

$\Delta E = f(B_0)$ Equation 2

The magnitude of the energy-level separation also depends on the particular nucleus involved. Each nucleus (hydrogen, chlorine, and so on) has a different ratio of magnetic moment to angular momentum since each has different charge and mass. This ratio, called the **magnetogyric ratio χ**, is a constant for each nucleus and determines the energy dependence on the magnetic field:

$\Delta E = f(\gamma B_0) = hv$ Equation 3

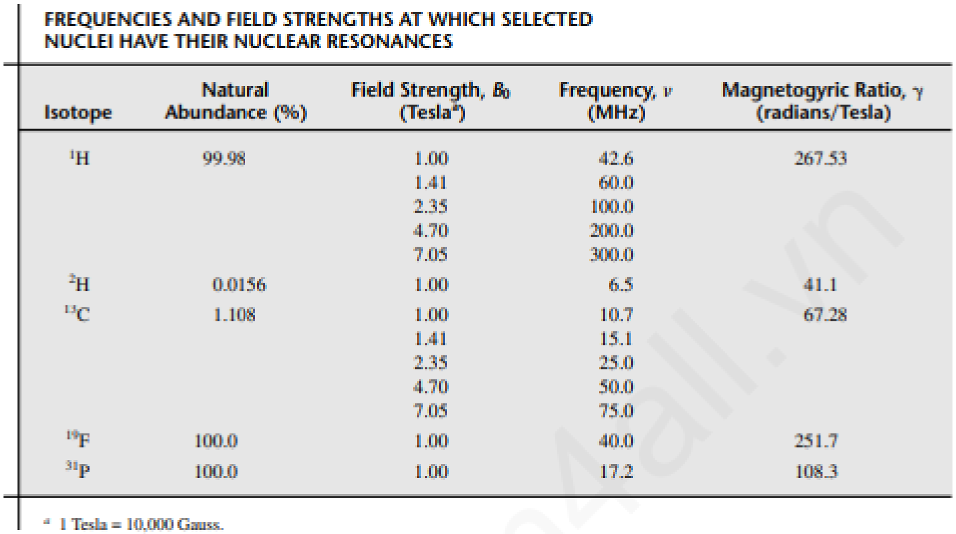
Since the angular momentum of the nucleus is quantized in units of h/2π, the final equation takes the form

$\Delta E = \gamma(h/2\pi)B_0 = hv$ Equation 4

Solving for the frequency of the absorbed energy,

$v = (\gamma/2\pi)B_0$ Equation 5

If the correct value of γ for the proton is substituted, one finds that an unshielded proton should absorb radiation of frequency 42.6 MHz in a field of strength 1 Tesla (10,000 Gauss) or radiation of frequency 60.0 MHz in a field of strength 1.41 Tesla (14,100 Gauss). Following table shows the field strengths and frequencies at which several nuclei have resonance (i.e., absorb energy and make spin transitions).



FREQUENCIES AND FIELD STRENGTHS AT WHICH SELECTED NUCLEI HAVE THEIR NUCLEAR RESONANCES

Isotope	Natural Abundance (%)	Field Strength, B_0 (Tesla[a])	Frequency, ν (MHz)	Magnetogyric Ratio, γ (radians/Tesla)
^{1}H	99.98	1.00	42.6	267.53
		1.41	60.0	
		2.35	100.0	
		4.70	200.0	
		7.05	300.0	
^{2}H	0.0156	1.00	6.5	41.1
^{13}C	1.108	1.00	10.7	67.28
		1.41	15.1	
		2.35	25.0	
		4.70	50.0	
		7.05	75.0	
^{19}F	100.0	1.00	40.0	251.7
^{31}P	100.0	1.00	17.2	108.3

[a] 1 Tesla = 10,000 Gauss.

Although many nuclei are capable of exhibiting magnetic resonance, the organic chemist is mainly interested in hydrogen and carbon resonances. We are not interested to discuss nuclei other than hydrogen—for example, carbon-13, fluorine-19, phosphorus-31, and deuterium (hydrogen-2).

For a proton (the nucleus of a hydrogen atom), if the applied magnetic field has a strength of approximately 1.41 Tesla, the difference in energy between the two spin states of the proton is about 2.39×10^{-5} kJ/mole. Radiation with a frequency of about 60 MHz (60,000,000 Hz), which lies in the radiofrequency (RF) region of the electromagnetic spectrum, corresponds to this energy difference. Other nuclei have both larger and smaller energy differences between spin states than do hydrogen nuclei. The earliest nuclear magnetic resonance spectrometers applied a variable magnetic field with a range of strengths near 1.41 Tesla and supplied a constant radiofrequency radiation of 60 MHz. They effectively induced transitions only among proton (hydrogen) spin states in a molecule and were not useful for other nuclei. Separate instruments were required to observe transitions in the nuclei of other elements, such as carbon and phosphorus. Fourier transform instruments, which are in common use today, are equipped to observe the nuclei of several different elements in a single instrument. Instruments operating at frequencies of 300 and 400 MHz are now quite common, and instruments with frequency higher than 600 MHz and found in larger research institutes.

D. THE MECHANISM OF ABSORPTION (RESONANCE):

To understand the nature of a nuclear spin transition, the analogy of a child's spinning top is useful. Protons absorb energy because they begin to precess in an applied magnetic field. The phenomenon of precession is similar to that of a spinning top. Owing to the influence of the earth's gravitational field, the top begins to "wobble," or precess, about its axis (Fig. a). A spinning nucleus behaves in a similar fashion under the influence of an applied magnetic field (Fig. b).

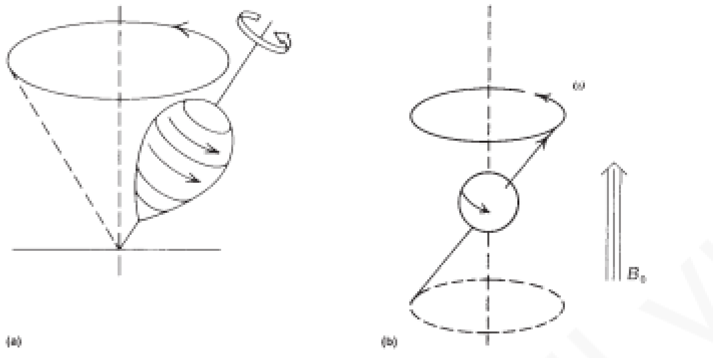


Fig. (a). a top precessing in the earth's gravitational field; (b) the precession of spinning nucleus resulting from the influence of an applied magnetic field.

When the magnetic field is applied, the nucleus begins to precess about its own axis of spin with angular frequency ω, which is sometimes called its **Larmor frequency**. The frequency at which a proton precesses is directly proportional to the strength of the applied magnetic field; the stronger the applied field, the higher the rate (angular frequency ω) of precession. For a proton, if the applied field is 1.41 Tesla (14,100 Gauss), the frequency of precession is approximately 60 MHz.

Since the nucleus has a charge, the precession generates an oscillating electric field of the same frequency. If radiofrequency waves of this frequency are supplied to the precessing proton, the energy can be absorbed. That is, **when the frequency of the oscillating electric field component of the incoming radiation just matches the frequency of the electric field generated by the precessing**

nucleus, the two fields can couple, and energy can be transferred from the incoming radiation to the nucleus, thus causing a spin change. This condition is called *resonance*, and the nucleus is said to have resonance with the incoming electromagnetic wave. Following figure schematically illustrates the resonance process.

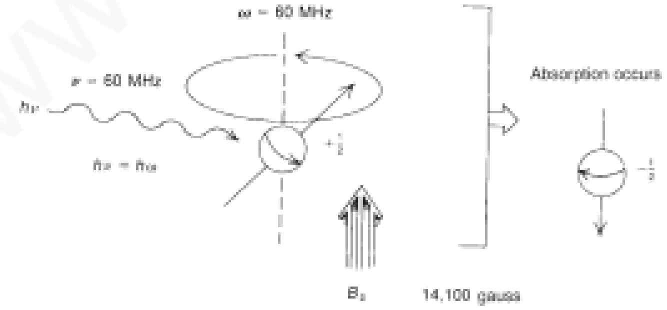


Fig. The nuclear magnetic resonance process; absorption occurs when ν = ω.

E. POPULATION DENSITIES OF NUCLEAR SPIN STATES

For a proton, if the applied magnetic field has a strength of approximately 1.41 Tesla, resonance occurs at about 60 MHz, and using E = hν, we can calculate that the difference in energy between the two spin states of the proton is about 2.39×10^{-5} kJ/mole. Thermal energy resulting from room temperature is sufficient to populate both of these energy levels since the energy separation between the two levels is small. There is, however, a slight excess of nuclei in the lower-energy spin state. The magnitude of this difference can be calculated using the Boltzmann distribution equations. Equation 3.7 gives the Boltzmann ratio of nuclear spins in the upper and lower levels.

Equation 3.7

$$\frac{\text{Nupper}}{\text{Nlower}} = e^{-\frac{\Delta E}{kT}} = e^{-\frac{h\nu}{kT}}$$

$$h = 6.624 \times 10^{-34} \text{ Jsec}$$

$$k = 1.380 \times 10^{-23} \text{ J/K - molecule}$$

$$T = \text{absolute temperature (K)}$$

where ΔE is the energy difference between the upper and lower energy states, and k is the molecular (not molar) gas constant. Since ΔE = hν, the second form of the equation is derived, where ν is the operating frequency of the instrument and h is Planck’s constant.

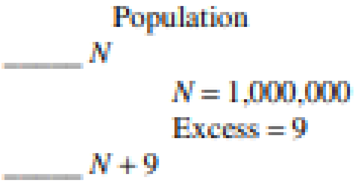
Using this Equation, one can calculate that at 298 K (25°C), for an instrument operating at 60 MHz there are 1,000,009 nuclei in the lower (favored) spin state for every 1,000,000 that occupy the upper spin state:

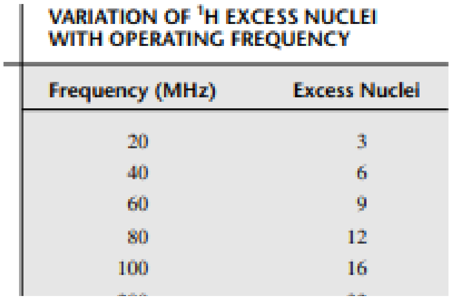
$$\frac{\text{Nupper}}{\text{Nlower}} = \frac{1000000}{1000009} = 0.999991$$

In other words, in approximately million nuclei, there are only 9 more nuclei in the lower spin state. Let us call this number (9) **the excess population** (Fig.).

The excess nuclei are the ones that allow us to observe resonance. When the 60-MHz radiation is applied, it not only induces transitions upward but also stimulates transitions downward. **If the populations of the upper and lower states become exactly equal, we observe no net signal. This situation is called saturation**. One must be careful to avoid saturation when performing an NMR experiment. Saturation is achieved quickly if the power of the radiofrequency signal is too high. Therefore, the very small excess of nuclei in the lower spin state is quite important to NMR spectroscopy, and we can see that very sensitive NMR instrumentation is required to detect the signal.

If we increase the operating frequency of the NMR instrument, the energy difference between the two states increases (see Fig.), which causes an increase in this excess. Table shows how the excess increases with operating frequency. It also clearly shows why modern instrumentation has been designed with increasingly higher operating frequencies. The sensitivity of the instrument is increased, and the resonance signals are stronger, because more nuclei can undergo transition at higher frequency. Before the advent of higher-field instruments, it was very difficult to observe less-sensitive nuclei such as carbon-13, which is not very abundant (1.1%) and has a detection frequency much lower than that of hydrogen (see Table).




VARIATION OF ^{1}H EXCESS NUCLEI WITH OPERATING FREQUENCY

Frequency (MHz)	Excess Nuclei
20	3
40	6
60	9
80	12
100	16

Fig. The excess of population of nuclei
in lower spin state at 60 MHz

Table: Table for variation

F. THE CHEMICAL SHIFT AND SHIELDING:

Nuclear magnetic resonance has great utility because not all protons in a molecule have resonance at exactly the same frequency. This variability is due to the fact that the protons in a molecule are surrounded by electrons and exist in slightly different electronic (magnetic) environments from one another. The valence-shell electron densities vary from one proton to another. The protons are shielded by the electrons that surround them. **In an applied magnetic field, the valence electrons of the protons are caused to circulate**. This circulation, called a **local diamagnetic current**, generates a counter magnetic field that opposes the applied magnetic field. Following Figure illustrates this effect, which is called **diamagnetic shielding or diamagnetic anisotropy**.

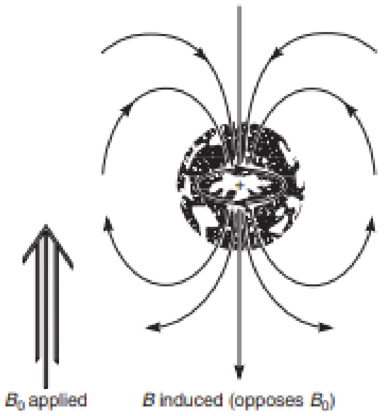


Fig. Diamagnetic anisotropy—the diamagnetic shielding of a nucleus caused by the circulation of valence electrons

Circulation of electrons around a nucleus can be viewed as being similar to the flow of an electric current in an electric wire. From physics, we know that the flow of a current through a wire induces a magnetic field. In an atom, the local diamagnetic current generates a secondary, induced magnetic field that has a different opposite that of the applied magnetic field.

As a result of diamagnetic anisotropy, each proton in a molecule is shielded from the applied magnetic field to an extent that depends on the electron density surrounding it. The greater the electron density around a nucleus, the greater the induced counter field that opposes the applied field. The counter field that shields a nucleus diminishes the net applied magnetic field that the nucleus experiences. As a result, the nucleus precesses at a lower frequency. This means that it also absorbs radiofrequency radiation at this lower frequency. Each proton in a molecule is in a slightly different chemical environment and consequently has a slightly different amount of electronic shielding, which results in a slightly different resonance frequency.

These differences in resonance frequency are very small. For instance, the difference between the resonance frequencies of the protons in chloromethane and those in fluoromethane is only 72 Hz when the applied field is 1.41 Tesla. Since the radiation used to induce proton spin transitions at that magnetic field strength is of a frequency near 60 MHz, the difference between chloromethane and fluoromethane represents a change in frequency of only slightly more than one part per million! It is very difficult to measure exact frequencies to that precision; hence, no attempt is made to measure the exact resonance frequency of any proton. Instead, a reference compound is placed in the solution of the substance to be measured, and the resonance frequency of each proton in the sample is measured relative to the resonance frequency of the protons of the reference substance. In other words, the frequency difference is measured directly. The standard reference substance that is used universally is **tetramethylsilane, $(CH_3)_4Si$**, also called **TMS**. This compound was chosen initially because the protons of its methyl groups are more shielded than those of most other known compounds. At that time, no compounds that had better-shielded hydrogens than TMS were known, and it was assumed that TMS would be a good reference substance since it would mark one end of the range. Thus, when another compound is measured, the resonances of its protons are reported in terms of how far (in Hertz) they are shifted from those of TMS.

The shift from TMS for a given proton depends on the strength of the applied magnetic field. In an applied field of 1.41 Tesla the resonance of a proton is approximately 60 MHz, whereas in an applied field of 2.35 Tesla (23,500 Gauss) the resonance appears at approximately 100 MHz. The ratio of the resonance frequencies is the same as the ratio of the two field strengths:

$$\frac{100\ \text{MHz}}{60\ \text{MHz}} = \frac{2.35\ \text{Tesla}}{1.41\ \text{Tesla}} = \frac{23500\ \text{Gauss}}{14100\ \text{Gauss}} = \frac{5}{3}$$

Hence, for a given proton, the shift (in Hertz) from TMS is $\frac{5}{3}$ larger in the 100-MHz range (B_0 = 2.35 Tesla) than in the 60-MHz range (B_0 = 1.41 Tesla). This can be confusing for workers trying to compare data if they have spectrometers that differ in the strength of the applied magnetic field. The confusion is easily overcome if one defines a new parameter that is independent of field strength—for instance, by dividing the shift in Hertz of a given proton by the frequency in megahertz of the spectrometer with which the shift value was obtained. In this manner, a field-independent measure called the **chemical shift (δ)** is obtained

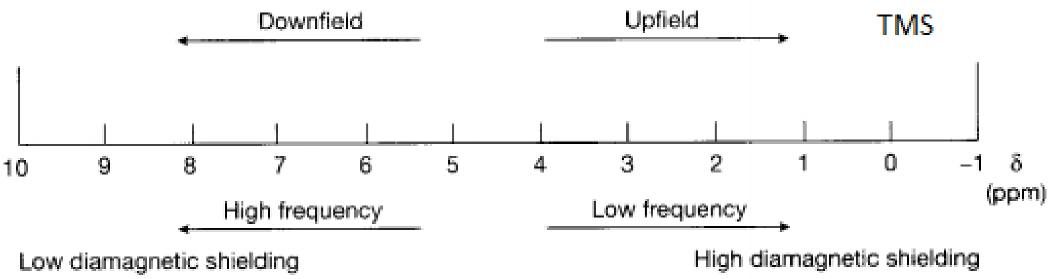
$$\delta = \frac{\text{(shift in Hz)}}{\text{(Spectrometer frequency in MHz)}}$$

The chemical shift in δ units expresses the amount by which a proton resonance is shifted from TMS, in parts per million (ppm), of the spectrometer's basic operating frequency. Values of d for a given proton are always the same irrespective of whether the measurement was made at 60 MHz (B_0 = 1.41 Tesla) or at 100 MHz (B_0 = 2.35 Tesla). For instance, at 60 MHz the shift of the protons in CH_3Br is 162 Hz from TMS, while at 100 MHz the shift is 270 Hz. However, both of these correspond to the same value of δ (2.70 ppm):

$$\delta = \frac{162\ \text{Hz}}{60\ \text{MHz}} = \frac{270\ \text{Hz}}{100\ \text{MHz}} = 2.70\ \text{ppm}$$

By agreement, most workers report chemical shifts in delta (δ) units, or parts per million (ppm), of the main spectrometer frequency. On this scale, the resonance of the protons in TMS comes at exactly 0.00 ppm (In TMS, the low electronegativity of silicon means that of protons and carbons are surrounded by a relatively high density of electrons. Hence, they are hifhly shielded and resonate at very low frequency. Shielding by silicon in fact is so strong that the proton and carbon resonances of TMS are placed at the right extreme of the spectrum, providing a convenient spectral zero).

The NMR spectrometer actually scans from high values to low ones (as will be discussed). Following is a typical chemical shift scale with the sequence of values that would be found on a typical NMR spectrum chart.



Chemical shift may express the difference in the resonance frequency of a given proton (atom) compared to that of the methyl protons of TMS, under the experimental condition. In practice;

$$\text{Chemical shift } (\delta) = \frac{\nu(s) - \nu(\text{TMS}) \text{ in Hz}}{\text{operating frequency in MHz}}$$

For example, if the observed shift from TMS is 200 Hz and the operating frequency of the instrument is 100 MHz, then the Chemical shift (δ) is given by the following expression

$$\text{Chemical shift } (\delta) = \frac{200 \text{ Hz}}{100 \text{ MHz}} = \frac{200 \text{ Hz}}{100 \times 10^{6} \text{ Hz}} = 2 \times 10^{-6}$$

This frequency ratio (2.0×10^{-6}) is multiplied by 10^6 in order to obtain an easily handled number ($2.0 \times 10^{-6} \times 10^{6} = 2.0$ ppm) and consequently the chemical shift (δ) is expressed as parts per million (10^{-6}) of the operating frequency, thus

$$\text{Chemical shift } (\delta) = \frac{\nu(s) - \nu(\text{TMS}) \text{ in Hz}}{\text{operating frequency of the instrument in MHz}} \times 10^{6} \text{ ppm}$$

Representation of Chemical shift: Chemical shift generally expressed in δ ppm, and this scale is called δ scale which is widely populated. G.V.D. Tiers proposed in 1958 an alternative chemical shift scale, known as τ scale, in which TMS is given an arbitrary value of 10 ppm. Thus

$$\tau = 10 - \delta \text{ ppm}$$

Internal standard:

The following compounds are generally taken as internal standard in NMR spectroscopy:

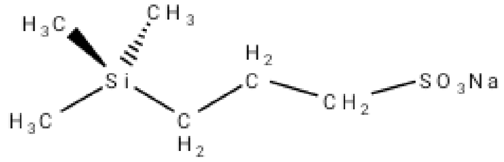
1. 

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

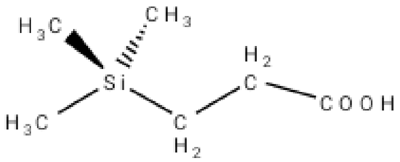
TMS is generally employed as internal standard for measuring the position of ^{1}H, ^{13}C and ^{29}Si in NMR spectrum because:

i). It gives a single sharp peak from magnetically twelve equivalent protons.
ii). It is chemically inert and miscible with large number of solvent.
iii). Being highly volatile, it can easily be removed if the sample is to be recovered.
iv). It does not involve in intermolecular association with the sample.
v). It has the added advantage that its resonance position is far removed from the absorption due to protons in most organic molecule.

2. For water soluble molecule, *Sodium salt of 3(trimethyl-silyl)propane-sulphonate* and *3(trimethyl-silyl)propanoic acid.* These are water soluble compound and used in D_2O solvent.



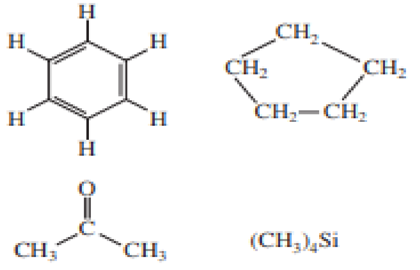
Sodium-3-(trimethylsilyl)propane-sulphonate

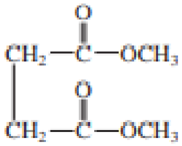
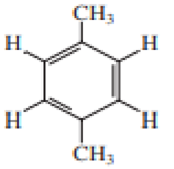
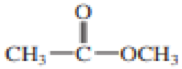
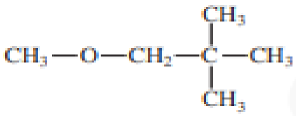


3-(trimethylsilyl)propanoic acid

G. Chemical Equivalence: A brief overview:

All of the protons found in chemically identical environments within a molecule are **chemically equivalent**, and they often exhibit the same chemical shift. Thus, all the protons in tetramethylsilane (TMS) or all the protons in benzene, cyclopentane, or acetone—which are molecules that have protons that are **equivalent** by ***symmetry considerations***—have resonance at a single value of δ (but a different value from that of each of the other molecules in the same group). Each such compound gives rise to a single absorption peak in its NMR spectrum. The protons are said to be chemically equivalent. On the other hand, a molecule that has sets of protons that are chemically distinct from one another may give rise to a different absorption peak from each set, in which case the sets of protons are chemically nonequivalent. The following examples should help to clarify these relationships:

	Molecules giving rise to one NMR absorption peak—all protons chemically equivalent

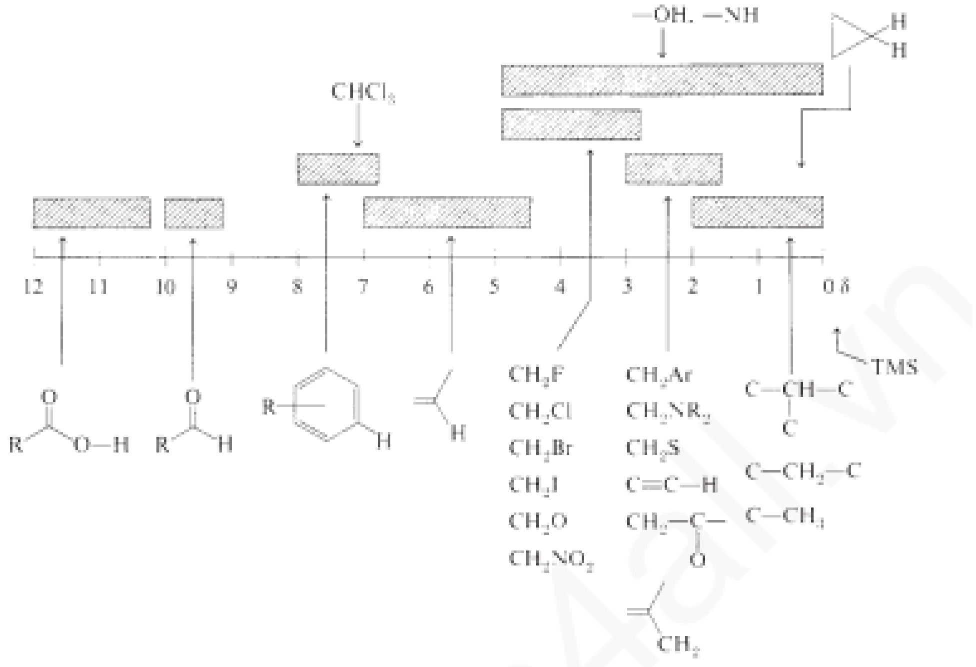
   $CH_3-\overset{O}{\overset{\Vert}{C}}-OCH_3$ CH_3-O-CH_2Cl	Molecules giving rise to two NMR absorption peaks—two different sets of chemically equivalent protons
 $CH_3-O-CH_2-C(CH_3)_2-CH_3$  $CH_3-\overset{O}{\overset{\Vert}{C}}-CH_2-O-CH_3$	Molecule giving rise to three NMR absorption peaks—three different sets of chemically equivalent protons

You can see that an NMR spectrum furnishes a valuable type of information on the basis of the number of different peaks observed; that is, the number of peaks corresponds to the number of chemically distinct types of protons in the molecule. Often, protons that are chemically equivalent are also magnetically equivalent. Note, however, that in some instances, *protons that are chemically equivalent are not magnetically equivalent*.

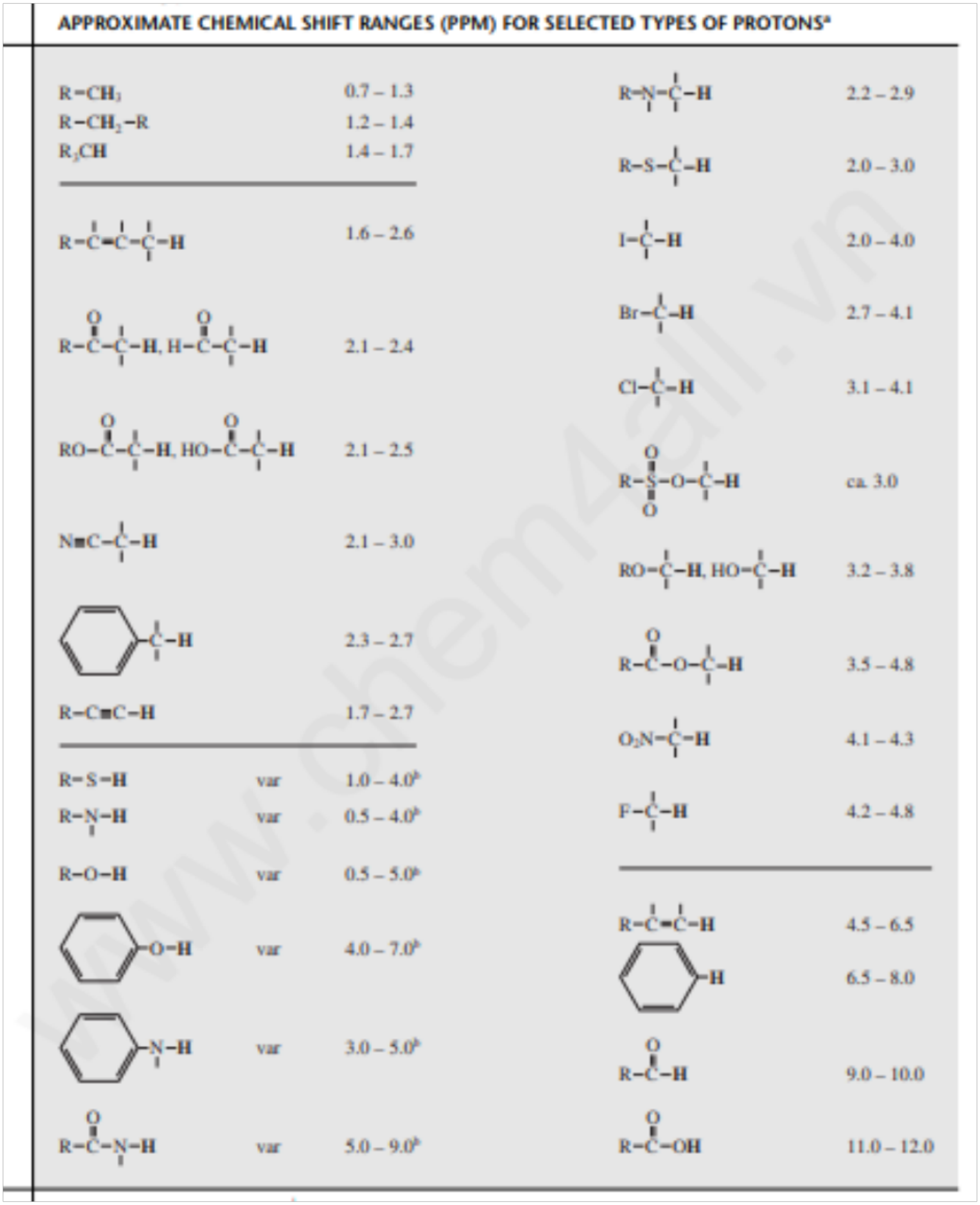
H. Chemical Environment and Chemical Shift:

If the resonance frequencies of all protons in a molecule were the same, NMR would be of little use to the organic chemist. Not only do different types of protons have different chemical shifts, but each also has a characteristic value of chemical shift. Every type of proton has only a limited range of δ values over which it gives resonance. Hence, the numerical value (in δ ppm) of the chemical shift for a proton gives a clue regarding the type of proton originating the signal, just as an infrared frequency gives a clue regarding the type of bond or functional group.

For instance, notice that the aromatic protons of both phenylacetone (Fig.) and benzyl acetate (Fig.) have resonance near 7.3 ppm, and that both of the methyl groups attached directly to a carbonyl have resonance at about 2.1 ppm. Aromatic protons characteristically have resonance near 7 to 8 ppm, whereas acetyl groups (methyl groups of this type) have their resonance near 2 ppm. These values of chemical shift are diagnostic. Notice also how the resonance of the benzyl ($-CH_2-$) protons comes at a higher value of chemical shift (5.1 ppm) in benzyl acetate than in phenylacetone (3.6 ppm). Being attached to the electronegative element oxygen, these protons are more deshielded (see Section) than those in phenylacetone. A trained chemist would readily recognize the probable presence of the oxygen from the value of chemical shift shown by these protons.



It is important to learn the ranges of chemical shifts over which the most common types of protons have resonance. Above Figure is a correlation chart that contains the most essential and frequently encountered types of protons. Table below lists the chemical shift ranges for selected types of protons. For the beginner, it is often difficult to memorize a large body of numbers relating to chemical shifts and proton types. One actually need do this only crudely. It is more important to "get a feel" for the regions and the types of protons than to know a string of actual numbers. To do this, study above Figure carefully. Following table and Apendix give more detailed of chemical shifts.



APPROXIMATE CHEMICAL SHIFT RANGES (PPM) FOR SELECTED TYPES OF PROTONS[a]

$R-CH_3$		0.7 – 1.3
$R-CH_2-R$		1.2 – 1.4
R_3CH		1.4 – 1.7
$R-C=C-C-H$		1.6 – 2.6
$R-\overset{O}{\overset{\|}{C}}-C-H$, $H-\overset{O}{\overset{\|}{C}}-C-H$		2.1 – 2.4
$RO-\overset{O}{\overset{\|}{C}}-C-H$, $HO-\overset{O}{\overset{\|}{C}}-C-H$		2.1 – 2.5
$N\equiv C-C-H$		2.1 – 3.0
⌬$-C-H$		2.3 – 2.7
$R-C\equiv C-H$		1.7 – 2.7
$R-S-H$	var	1.0 – 4.0[b]
$R-N-H$	var	0.5 – 4.0[b]
$R-O-H$	var	0.5 – 5.0[b]
⌬$-O-H$	var	4.0 – 7.0[b]
⌬$-N-H$	var	3.0 – 5.0[b]
$R-\overset{O}{\overset{\|}{C}}-N-H$	var	5.0 – 9.0[b]
$R-N-C-H$		2.2 – 2.9
$R-S-C-H$		2.0 – 3.0
$I-C-H$		2.0 – 4.0
$Br-C-H$		2.7 – 4.1
$Cl-C-H$		3.1 – 4.1
$R-\overset{O}{\underset{O}{S}}-O-C-H$		ca. 3.0
$RO-C-H$, $HO-C-H$		3.2 – 3.8
$R-\overset{O}{\overset{\|}{C}}-O-C-H$		3.5 – 4.8
O_2N-C-H		4.1 – 4.3
$F-C-H$		4.2 – 4.8
$R-C=C-H$		4.5 – 6.5
⌬$-H$		6.5 – 8.0
$R-\overset{O}{\overset{\|}{C}}-H$		9.0 – 10.0
$R-\overset{O}{\overset{\|}{C}}-OH$		11.0 – 12.0

[a] For those hydrogens shown as –C-H, if that hydrogen is part of a methyl group (CH_3) the shift is generally at the low end of the range given, if the hydrogen is in a methylene group ($-CH_2-$) the shift is intermediate, and if the hydrogen is in a methine group (-C-H), the shift is typically at the high end of the range given.

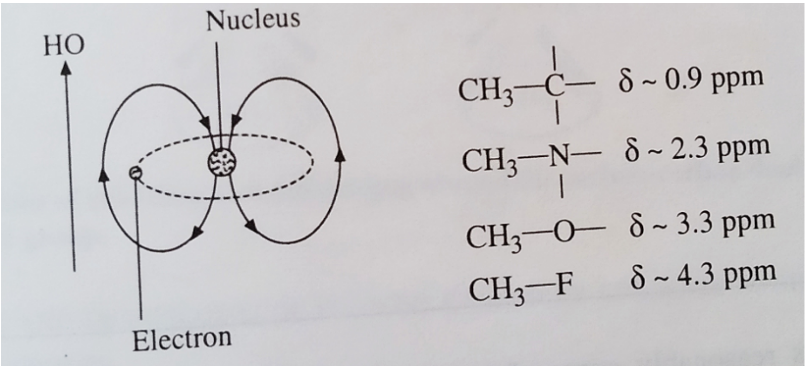
[b] The chemical shift of these groups is variable, depending not only on the chemical environment

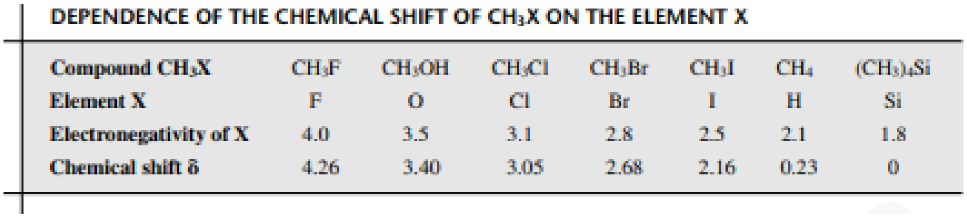
in the molecule, but also on concentration, temperature, and solvent.

I. Local Effect:

i). Electronegativity Effect:

The term of chemical shifts that 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 increases as the electronegativity of the attached element increases. Following Table illustrates this relationship for several compounds of the type CH_3X.

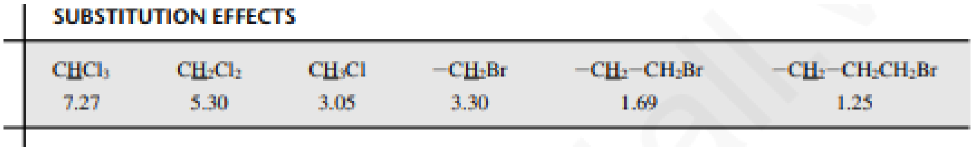




DEPENDENCE OF THE CHEMICAL SHIFT OF CH_3X ON THE ELEMENT X

Compound CH_3X	CH_3F	CH_3OH	CH_3Cl	CH_3Br	CH_3I	CH_4	$(CH_3)_4Si$
Element X	F	O	Cl	Br	I	H	Si
Electronegativity of X	4.0	3.5	3.1	2.8	2.5	2.1	1.8
Chemical shift δ	4.26	3.40	3.05	2.68	2.16	0.23	0

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 that are more than three carbons distant. Following Table illustrates these effects for the underlined protons.



SUBSTITUTION EFFECTS

$C\underline{H}Cl_3$	$C\underline{H}_2Cl_2$	$C\underline{H}_3Cl$	$-C\underline{H}_2Br$	$-C\underline{H}_2-CH_2Br$	$-C\underline{H}_2-CH_2CH_2Br$
7.27	5.30	3.05	3.30	1.69	1.25

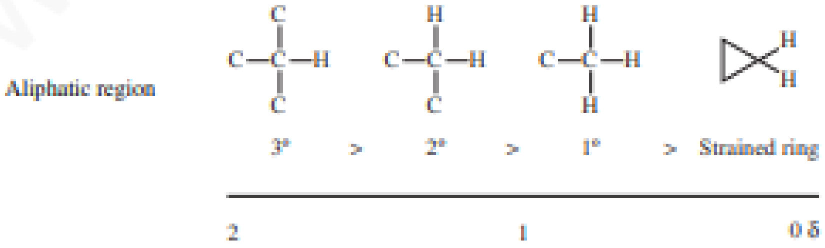
Later Section briefly discussed the origin of the electronegativity effect. Electronegative substituents attached to a carbon atom, because of their electron-withdrawing effects, reduce the valence electron density around the protons attached to that carbon. These electrons, it will be recalled, shield the proton from the applied magnetic field. Figure illustrates this effect, called local diamagnetic shielding. Electronegative 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 that have this type of effect are said to deshield the proton. The greater the electronegativity of the substituent, the more it deshields protons and hence the greater is the chemical shift of those protons.

ii). Hybridization Effects:

The second important set of trends is that due to difference in the hybridization of the atom to which hydrogen is attached.

sp^3 Hydrogens

Referring to Fig. and Table, notice that all hydrogens attached to purely sp^3 carbon atoms ($C-CH_3$, $C-CH_2-C$, C-CH-C, cycloalkanes) have resonance in the limited range from 0 to 2 ppm, provided that no electronegative elements or π-bonded groups are nearby. At the extreme right of this range are TMS (0 ppm) and hydrogens attached to carbons in highly strained rings (0–1 ppm)—as occurs, for example, with cyclopropyl hydrogens. Most methyl groups occur near 1 ppm if they are attached to other sp^3 carbons. Methylene-group hydrogens (attached to sp^3 carbons) appear at greater chemical shifts (near 1.2 to 1.4 ppm) than do methyl-group hydrogens. Tertiary methine hydrogens occur at higher chemical shift than secondary hydrogens, which in turn have a greater chemical shift than do primary or methyl hydrogens. The following diagram illustrates these relationships:



Of course, hydrogens on an sp^3 carbon that is attached to a heteroatom ($-O-CH_2-$, and so on) or to an unsaturated carbon ($-C=C-CH_2-$) do not fall in this region but have greater chemical shifts.

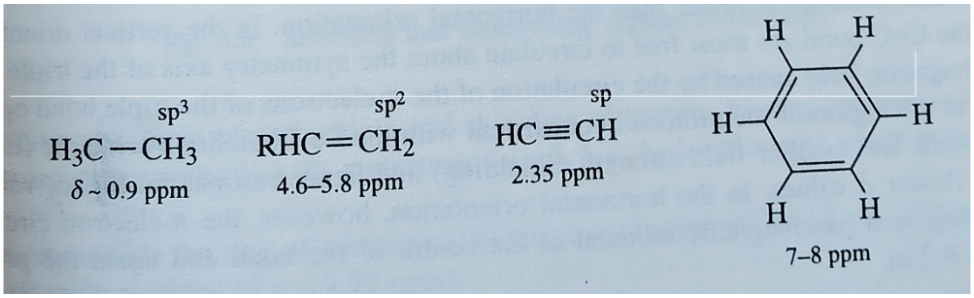
sp^2 Hydrogens

Simple vinyl hydrogens (-C=C-H) have resonance in the range from 4.5 to 7 ppm. In an sp^2 -1s C-H bond, the carbon atom has more s character (33% s), which effectively renders it "more electronegative" than an sp^3 carbon (25% s). Remember that s orbitals hold electrons closer to the nucleus than do the carbon p orbitals. If the sp^2 carbon atom holds its electrons more tightly, this results in less shielding for the H nucleus than in an sp^3 -1s bond. Thus, vinyl hydrogens have a greater chemical shift (5 to 6 ppm) than aliphatic hydrogens on sp^3 carbons (1 to 4 ppm). Aromatic hydrogens appear in a range farther downfield (7 to 8 ppm). The downfield positions of vinyl and aromatic resonances are, however, greater than one would expect based on these hybridization differences.

Another effect, called **anisotropy**, is responsible for the largest part of these shifts (and will be discussed in latter). Aldehyde protons (also attached to sp^2 carbon) appear even farther downfield (9 to 10 ppm) than aromatic protons since the inductive effect of the electronegative oxygen atom further decreases the electron density on the attached proton. Aldehyde protons, like aromatic and alkene protons, exhibit an anomalously large chemical shift due to anisotropy.

sp Hydrogens

Acetylenic hydrogens (C-H, sp-1s) appear anomalously at 2 to 3 ppm owing to anisotropy (to be discussed). On the basis of hybridization alone, as already discussed, one would expect the acetylenic proton to have a chemical shift greater than that of the vinyl proton. An *sp* carbon should behave as if it were more electronegative than an sp^2 carbon. This is the opposite of what is actually observed.



iii). Acidic and Exchangeable Proton;

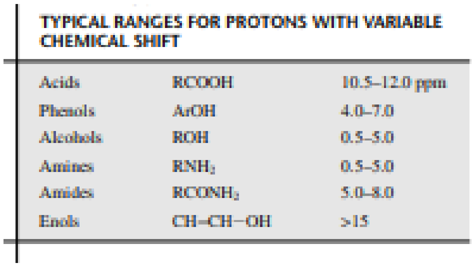
Acidic Hydrogens

Some of the least-shielded protons are those attached to carboxylic acids. These protons have their resonances at 10 to 12 ppm.

Both resonance and the electronegativity effect of oxygen withdraw electrons from the acid proton.

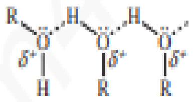
Hydrogen Bonding and Exchangeable Hydrogens

Protons that can exhibit hydrogen bonding (e.g., hydroxyl or amino protons) exhibit extremely variable absorption positions over a wide range. They are usually found attached to a heteroatom. In Table lists the ranges over which some of these types of protons are found. The more hydrogen bonding that takes place, the more deshielded a proton becomes.

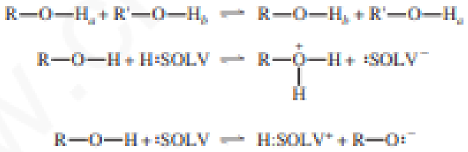


TYPICAL RANGES FOR PROTONS WITH VARIABLE CHEMICAL SHIFT		
Acids	RCOOH	10.5–12.0 ppm
Phenols	ArOH	4.0–7.0
Alcohols	ROH	0.5–5.0
Amines	RNH_2	0.5–5.0
Amides	$RCONH_2$	5.0–8.0
Enols	CH=CH–OH	>15

Free (dilute solution)



Hydrogen bonded (concentrated solution)



$$R-O-H_a + R'-O-H_b \rightleftharpoons R-O-H_b + R'-O-H_a$$

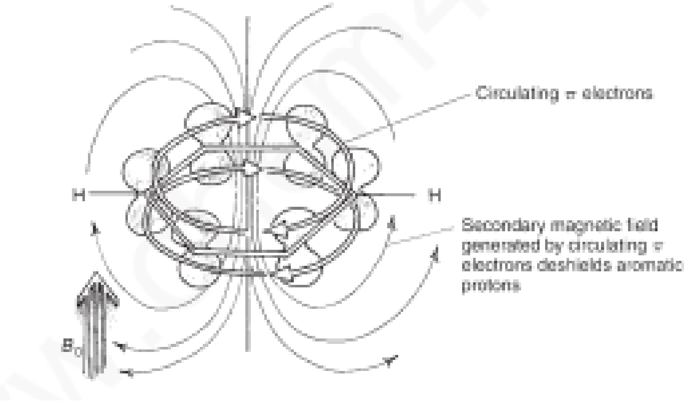
$$R-O-H + H{:}SOLV \rightleftharpoons R-\underset{\displaystyle H}{\overset{+}{O}}-H + {:}SOLV^-$$

$$R-O-H + {:}SOLV \rightleftharpoons H{:}SOLV^+ + R-O{:}^-$$

MAGNETIC ANISOTROPY:

Previous figure clearly shows that there are some types of protons with chemical shifts that are not easily explained by simple considerations of the electronegativity of the attached groups. For instance, consider the protons of benzene and other aromatic systems. Aryl protons generally have a chemical shift as large as that of the proton of chloroform! Alkenes, alkynes, and aldehydes also have protons with resonance values that are not in line with the expected magnitudes of any electron-withdrawing or hybridization effects. In each of these cases, the anomalous shift is due to the presence of an unsaturated system (one with π electrons) in the vicinity of the proton in question.

Take benzene, for example. When it 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 generated 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. Following Figure illustrates this phenomenon.



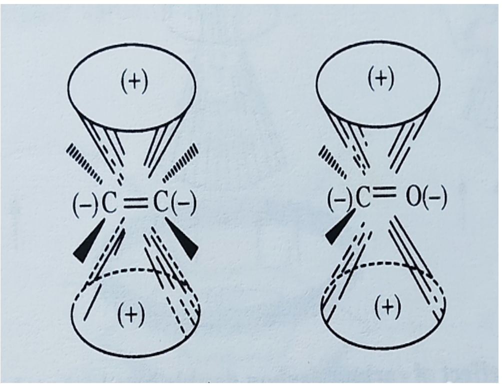
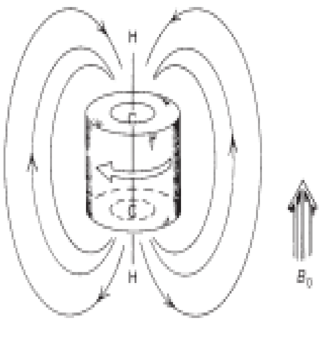


Fig. Diamagnetic anisotropy and ring current

The benzene hydrogens are said to be deshielded by the diamagnetic anisotropy of the ring. 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 non uniform. An applied magnetic field is anisotropic in the vicinity of a benzene molecule because the labile electrons in the ring interact with the applied field. This creates a non-homogeneity in the immediate vicinity of the molecule. **Thus, a proton attached to a benzene ring is influenced by three magnetic fields**: the strong magnetic field applied by the electromagnets 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. It is the anisotropic effect that gives the benzene protons a chemical shift that is greater than expected. These protons just happen to lie in a deshielding region of the 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 since the field lines there would have the opposite direction from those at the periphery.

All groups in a molecule that have π electrons generate secondary anisotropic fields. In acetylene, the magnetic field generated by induced circulation of the π electrons has a geometry such that the acetylenic hydrogens are shielded (Fig.). Hence, acetylenic hydrogens have resonance at higher field than expected. The shielding and deshielding regions due to the various π electron functional groups have characteristic shapes and directions, and following Figure illustrates these for a number of groups. Protons falling within the conical areas are shielded, and those falling outside the conical areas are deshielded. The magnitude of the anisotropic field diminishes with distance, and beyond a certain distance there is essentially no anisotropic effect. Following Figure shows the effects of anisotropy in several actual molecules.



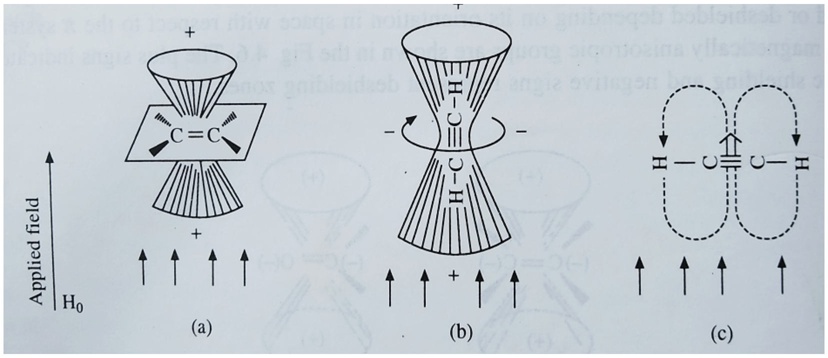


Fig. Diamagnetic anisotropy in acetylene

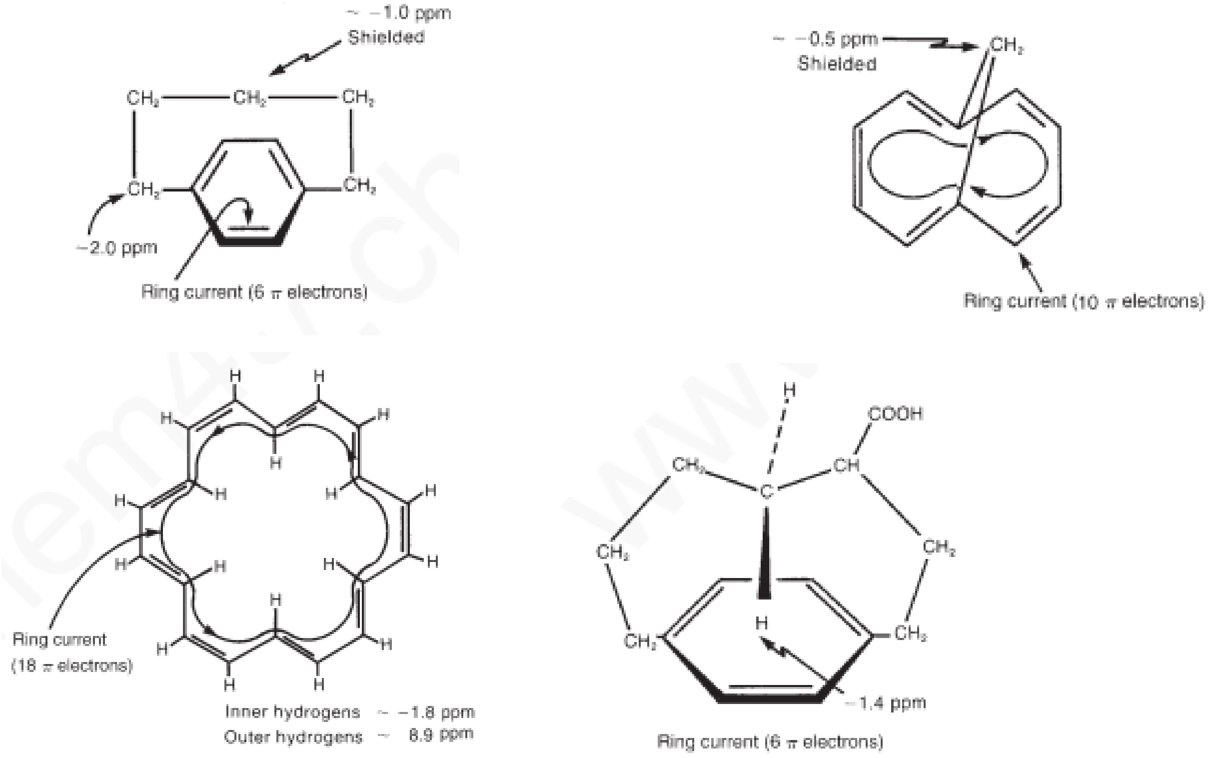
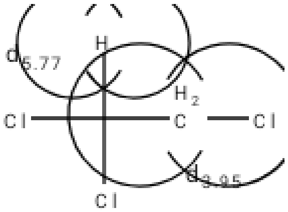


Fig. The effects of anisotropy in some actual molecules.

SPIN–SPIN SPLITTING (n+1) RULE:

We have discussed the manner in which the chemical shift and the integral (peak area) can give information about the number and types of hydrogens contained in a molecule. A third type of information to be found in the NMR spectrum is that derived from the spin–spin splitting phenomenon. Even in simple molecules, one finds that each type of proton rarely gives a single resonance peak. For instance, in 1,1,2-trichloroethane there are two chemically distinct types of hydrogens:



On the basis of the information given thus far, one would predict two resonance peaks in the NMR spectrum of 1,1,2-trichloroethane, with an area ratio (integral ratio) of 2:1. In reality, the high-resolution NMR spectrum of this compound has five peaks: a group of three peaks (called a **triplet**) at 5.77 ppm and a group of two peaks (called a **doublet**) at 3.95 ppm. Following Figure shows this spectrum. The methine (CH) resonance (5.77 ppm) is said to be split into a triplet, and the methylene resonance (3.95 ppm) is split into a doublet. The area under the three triplet peaks is 1, relative to an area of 2 under the two doublet peaks.

This phenomenon, **called spin–spin splitting**, can be explained empirically by the so-called **n + 1 Rule**. Each type of proton “*senses*” the number of equivalent protons (n) on the carbon atom(s) next to the one to which it is bonded, and its resonance peak is split into (n + 1) components.

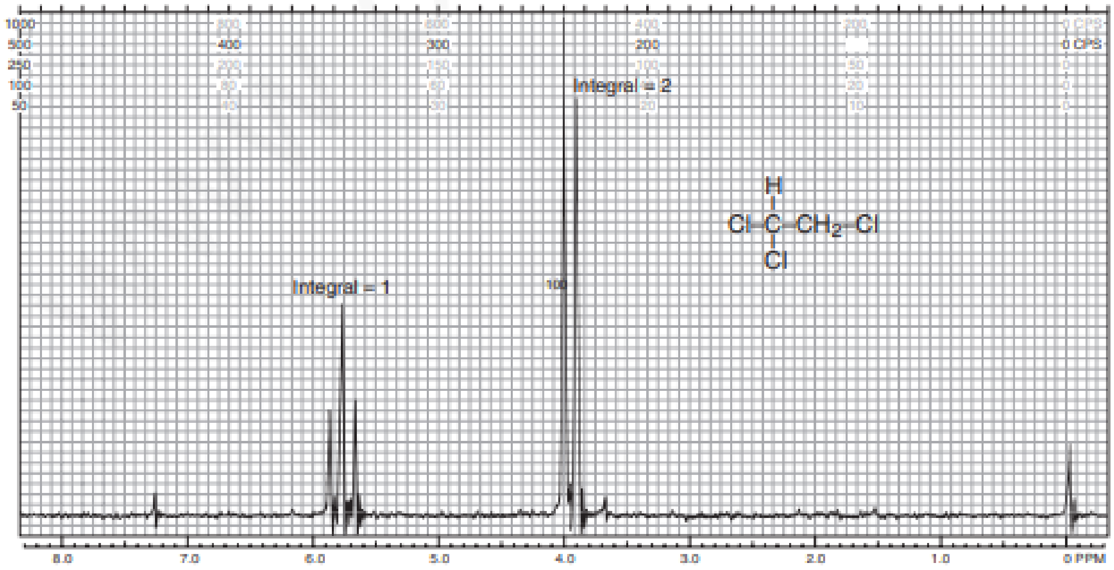
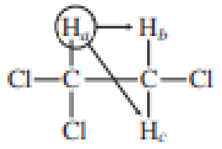
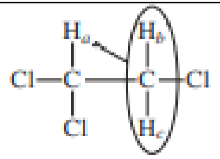
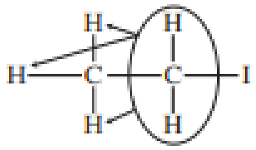
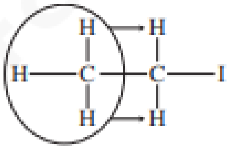


FIGURE : The ^{1}H-NMR spectrum of 1,1,2-trichloroethane (60 MHz).

Examine the case at hand, 1,1,2-trichloroethane, utilizing the n + 1 Rule. First the lone methine hydrogen is situated next to a carbon bearing two methylene protons. According to the rule, it has two equivalent neighbors (n = 2) and is split into n + 1 = 3 peaks (a **triplet**). The methylene protons are situated next to a carbon bearing only one methine hydrogen. According to the rule, these protons have one neighbor (n = 1) and are split into n + 1 = 2 peaks (a **doublet**).

	
Two neighbors give a triplet (n + 1 = 3) (area = 1)	One neighbor gives a doublet (n + 1 = 2) (area = 2)

Before proceeding to explain the origin of this effect, let us examine two simpler cases predicted by the n + 1 Rule. Following Figure is the spectrum of ethyl iodide (CH_3CH_2I). Notice that the methylene protons are split into a quartet (four peaks), and the methyl group is split into a triplet (three peaks). This is explained as follows:

	
Three equivalent neighbors give a quartet (n + 1 = 4) (area = 2)	Two equivalent neighbors give a triplet (n + 1 = 3) (area = 3)

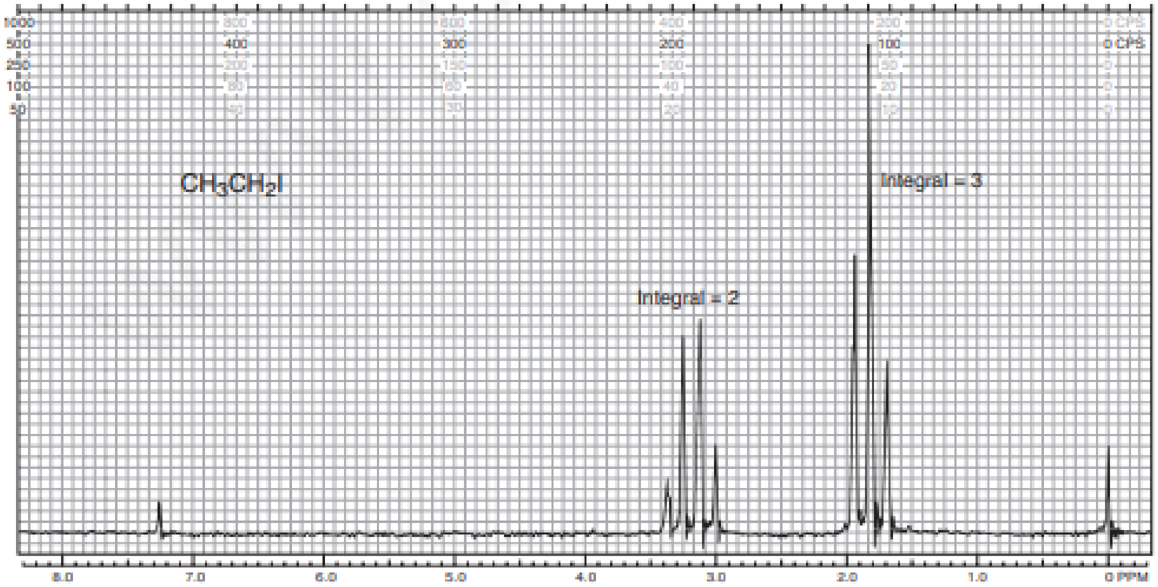
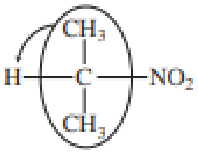
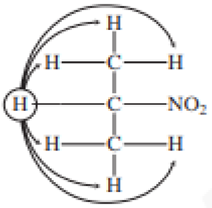


Fig: The ^{1}H-NMR spectrum of ethyl iodide (60 MHz)

Finally, consider 2-nitropropane, which has the spectrum given in given Figure.

Notice that in the case of 2-nitropropane there are two adjacent carbons that bear hydrogens (two carbons, each with three hydrogens), and that all six hydrogens as a group split the methine hydrogen into a septet.

	
One neighbor gives a doublet (n + 1 = 2) (area = 6)	Six equivalent neighbors give a septet (n + 1 = 7) (area = 1)

Also notice that the chemical shifts of the various groups of protons make sense according to the discussions in respective Sections. Thus, in 1,1,2-trichloroethane, the methine hydrogen (on a carbon bearing two Cl atoms) has a larger chemical shift than the methylene protons (on a carbon bearing only one Cl atom). In ethyl iodide, the hydrogens on the carbon-bearing iodine have a larger chemical shift than those of the methyl group. In 2-nitropropane, the methine proton (on the carbon bearing the nitro group) has a larger chemical shift than the hydrogens of the two methyl groups.

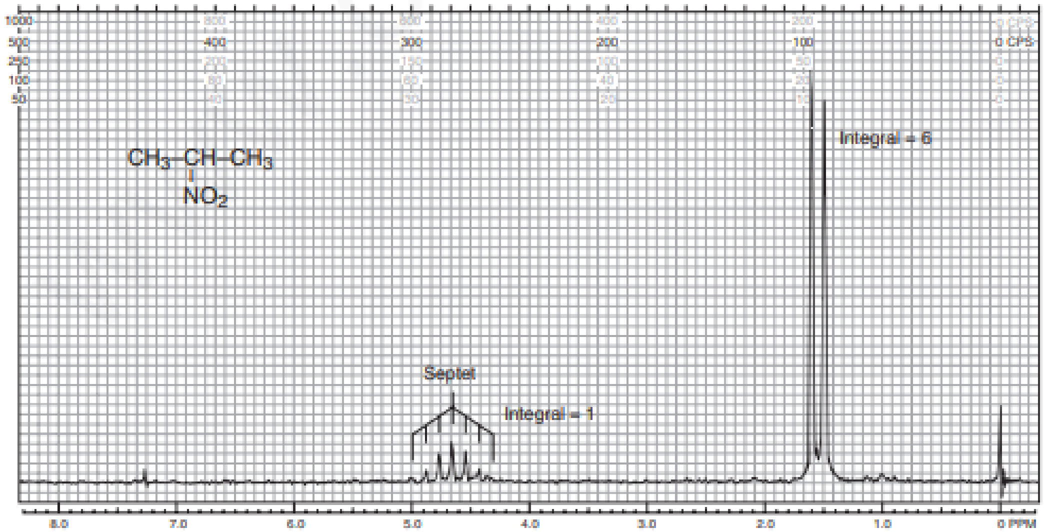
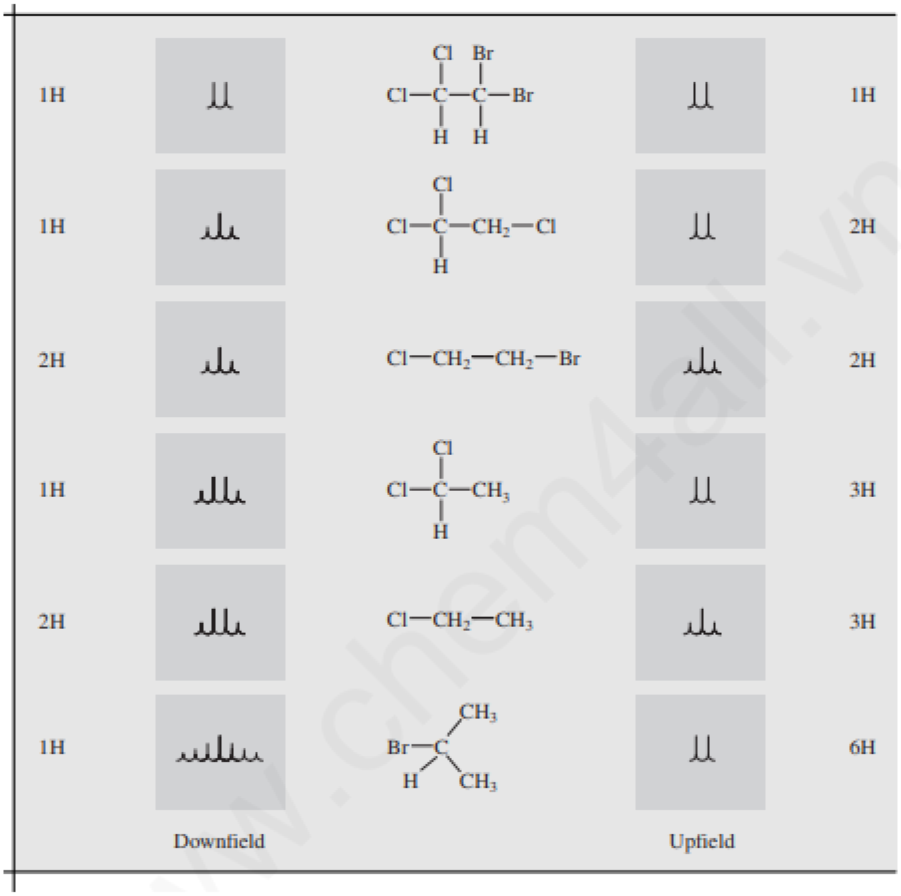


Fig. The ^{1}H-NMR spectrum of 2-nitropropane (60 MHz).

Finally, note that the spin–spin splitting gives a new type of structural information. It reveals how many hydrogens are adjacent to each type of hydrogen that is giving an absorption peak or, as in these cases, an absorption multiplet. For reference, some commonly encountered spin–spin splitting patterns are collected in the given Table

Table: SOME EXAMPLES OF COMMONLY OBSERVED SPLITTING PATTERNS IN COMPOUNDS

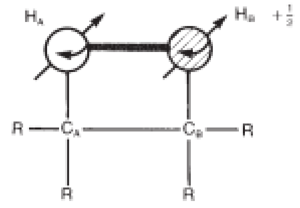
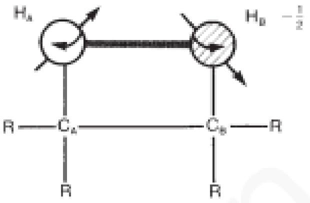


The Origin of Spin-Spin Splitting:

Spin-spin splitting arises because hydrogens on adjacent carbon atoms can “sense” one another. The hydrogen on carbon A can sense the spin direction of the hydrogen on carbon B. In some molecules of the solution, the hydrogen on carbon B has spin $+\frac{1}{2}$ (X-type molecules); in other molecules of the solution, the hydrogen on carbon B has spin $-\frac{1}{2}$ (Y-type molecules). Given Figure illustrates these two types of molecules.

The chemical shift of proton A is influenced by the direction of the spin in proton B. Proton A is said to be **coupled** to proton B. Its magnetic environment is affected by whether proton B has a $+\frac{1}{2}$ or a $-\frac{1}{2}$ spin state. Thus, proton A absorbs at a slightly different chemical shift value in type X molecules than in type Y molecules. In fact, in X-type molecules, proton A is slightly deshielded because the field of proton B is aligned with the applied field, and its magnetic moment adds to the applied field. In Y-type molecules, proton A is slightly shielded with respect to what its chemical shift would be in the absence of coupling. In this latter case, the field of proton B diminishes the effect of the applied field on proton A.

Since in a given solution there are approximately equal numbers of X- and Y-type molecules at any given time, two absorptions of nearly equal intensity are observed for proton A. The resonance of proton A is said to have been split by proton B, and the general phenomenon is **called spin–spin splitting**. Given fig. summarizes the spin–spin splitting situation for proton A.

<table>
<tr><td> </td><td> </td></tr>
<tr><td>X-type molecule</td><td>Y-Type molecule</td></tr>
<tr><td colspan="2">Fig.: Two different molecules in a solution with differing spin relationships between protons H_A and H_B.</td></tr>
</table>

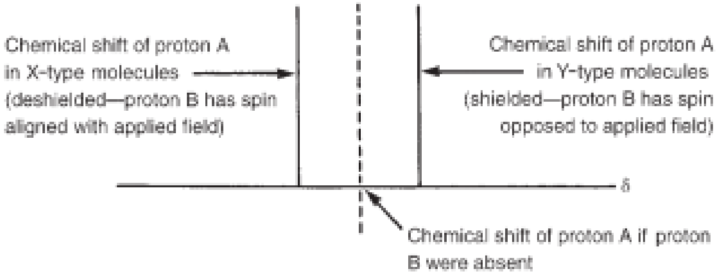
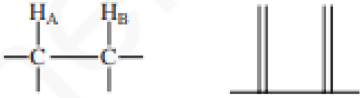
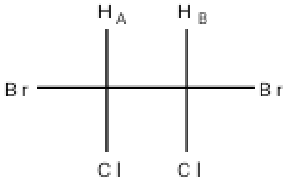


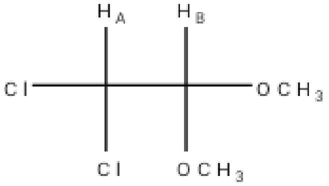
Fig.: The origin of spin–spin splitting in proton A’s NMR spectrum.

Of course, proton A also “*splits*” proton B since proton A can adopt two spin states as well. The final spectrum for this situation consists of two doublets:



Two doublets will be observed in any situation of this type except one in which protons A and B are identical by symmetry, as in the case of the first of the following molecules:





The first molecule would give only a single NMR peak since protons A and B have the same chemical shift value and are, in fact, identical. The second molecule would probably exhibit the two-doublet spectrum since proton A and B are not identical and would surely have different chemical shift.

Now consider **ethyl iodide**, which has the spectrum shown in Figure. The methyl protons give rise to a triplet centered at 1.83 ppm, and the methylene protons give a quartet centered at 3.20 ppm. This pattern and the relative intensities of the component peaks can be explained with the use of the model for the two-proton case outlined. First, look at the methylene protons and their pattern, which is a quartet. The methylene protons are split by the methyl protons, and to understand the splitting pattern, you must examine the various possible spin arrangements of the protons for the methyl group, which are shown in Figure.

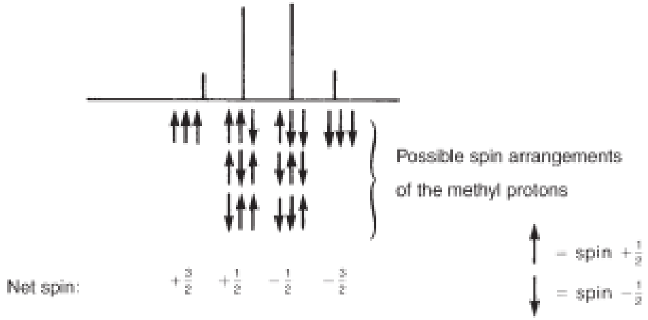


Fig.: The splitting pattern of methylene protons due to the presence of an adjacent methyl group

Some of the eight possible spin arrangements are identical to each other since one methyl proton is indistinguishable from another and since there is free rotation in a methyl group. Taking this into consideration, there are only four different types of arrangements. There are, however, three possible ways to obtain the arrangements with net spins of $+\frac{1}{2}$ and $-\frac{1}{2}$. Hence, these arrangements are three times more probable statistically than are the $+\frac{3}{2}$ and $-\frac{3}{2}$ spin arrangements. Thus, one notes in the splitting pattern of the methylene protons that the center two peaks are more intense than the outer ones. In fact, the intensity ratios are 1:3:3:1. Each of these different spin arrangements of the methyl protons (except the sets of degenerate ones, which are effectively identical) gives the methylene protons in that molecule a different chemical shift value. Each of the spins in the $+\frac{1}{2}$ arrangement tends to deshield the methylene proton with respect to its position in the absence of coupling. The $+\frac{1}{2}$ arrangement also deshields the methylene proton, but only slightly, since the two opposite spins cancel each other's effects. The $-\frac{1}{2}$ arrangement shields the methylene proton slightly, whereas the $-\frac{3}{2}$ arrangement shields the methylene proton more strongly.

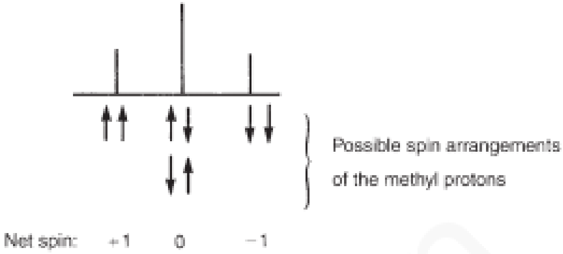


Fig.: The splitting pattern of methyl protons due to the presence of an adjacent methylene group

Keep in mind that there are actually four different "*types*" of molecules in the solution, each type having a different methyl spin arrangement. Each spin arrangement causes the methylene protons in that molecule to have a chemical shift different from those in a molecule with another methyl spin arrangement (except, of course, when the spin arrangements are indistinguishable, or degenerate). Molecules having the $+\frac{1}{2}$ and $-\frac{1}{2}$ spin arrangements are three times more numerous in solution than those with the $+\frac{3}{2}$ and $-\frac{3}{2}$ spin arrangements. Figure provides a similar analysis of the methyl splitting pattern, showing the four possible spin arrangements of the methylene protons. Examination of this figure makes it easy to explain the origin of the triplet for the methyl group and the intensity ratios of 1:2:1.

Now one can see the origin of the ethyl pattern and the explanation of its intensity ratios. The occurrence of spin–spin splitting is very important for the organic chemist as it gives additional structural information about molecules. Namely, it reveals the number of nearest proton neighbors each type of proton has. From the chemical shift one can determine what type of proton is being split, and from the integral (the area under the peaks) one can determine the relative numbers of the types of hydrogen. This is a great amount of structural information.

PASCAL'S TRIANGLE:

We can easily verify that the intensity ratios of multiplets derived from the n + 1 Rule follow the entries in the mathematical mnemonic device called Pascal's triangle (Fig.). Each entry in the triangle is the sum of the two entries above it and to its immediate left and right. Notice that the intensities of the outer peaks of a multiplet such as a septet are so small compared to the inner peaks that they are often obscured in the baseline of the spectrum.

Singlet	1
Doublet	1 1
Triplet	1 2 1
Quartet	1 3 3 1
Quintet	1 4 6 4 1
Sextet	1 5 10 10 5 1
Septet	1 6 15 20 15 6 1

Fig. Pascal’s triangle.

THE COUPLING CONSTANT

Previous section discussed the splitting pattern of the ethyl group and the intensity ratios of the multiplet components but did not address the quantitative amount by which the peaks were split. *The distance between the peaks in a simple multiplet is called the* ***coupling constant J***. The coupling constant is a measure of how strongly a nucleus is affected by the spin states of its neighbor. The spacing between the multiplet peaks is measured on the same scale as the chemical shift, and the coupling constant is always expressed in Hertz (Hz). In ethyl iodide, for instance, the coupling constant J is 7.5 Hz. To see how this value was determined, consult following figure.

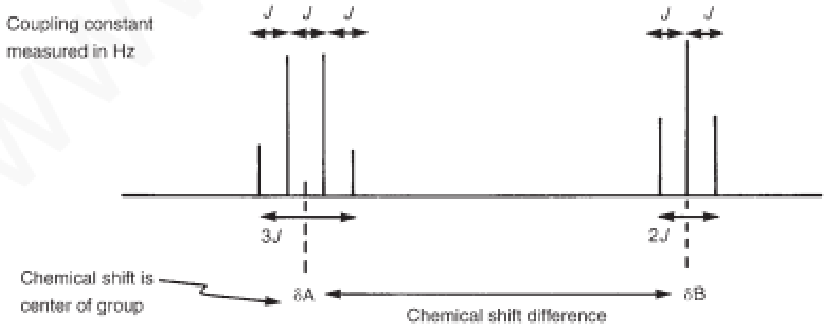


Fig.: The definition of the coupling constants in the ethyl splitting pattern.

The spectrum of ethyl iodide was determined at 60 MHz; thus, each ppm of chemical shift (δ unit) represents 60 Hz. Inasmuch as there are 12 grid lines per ppm, each grid line represents (60 Hz)/12 = 5 Hz. Notice the top of the spectrum. It is calibrated in cycles per second (cps), which are the same as Hertz, and since there are 20 chart divisions per 100 cps, one division equals (100 cps)/20 = 5 cps = 5 Hz. Now examine the multiplets. The spacing between the component peaks is approximately 1.5 chart divisions, so

$$J = 1.5 \text{ div} \times \frac{5\text{Hz}}{1\text{div}} = 7.5 \text{ Hz}$$

That is, the coupling constant between the methyl and methylene protons is 7.5 Hz. When the protons interact, the magnitude (in ethyl iodide) is always of this same value, 7.5 Hz. The amount of coupling is constant, and hence J can be called a coupling constant.

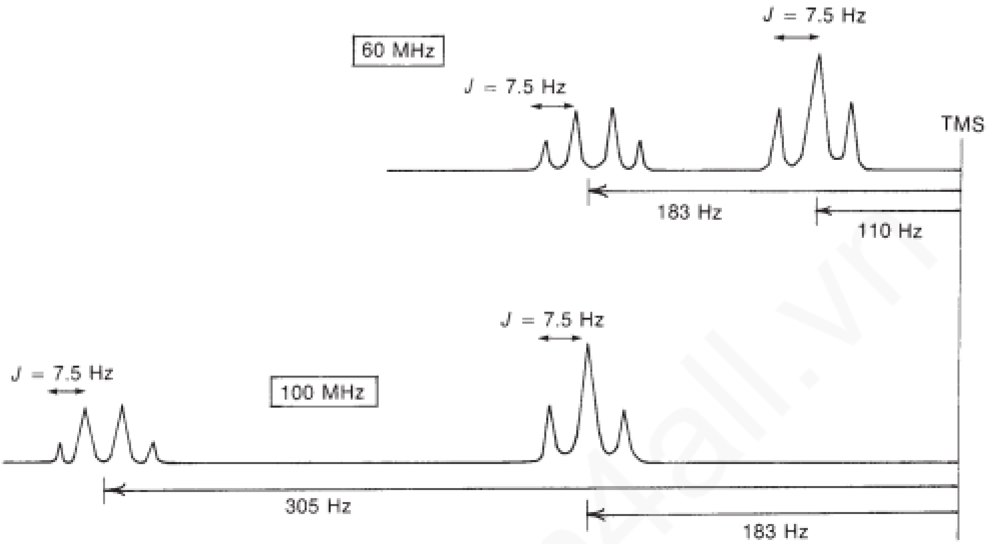
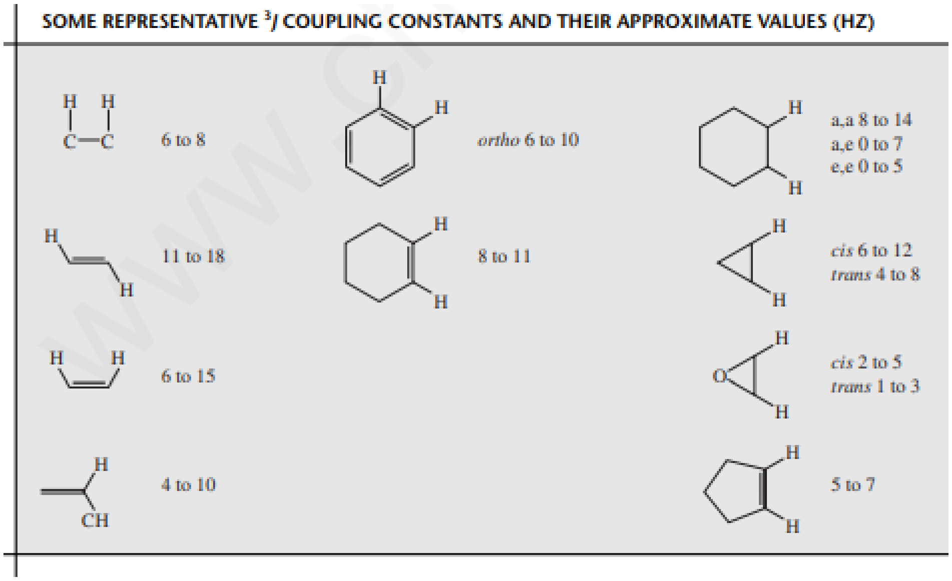


Fig. An illustration betwn. Chemical shift, coupling constant with instrumental capacity

The invariant nature of the coupling constant can be observed when the NMR spectrum of ethyl iodide is determined at both 60 MHz and 100 MHz. A comparison of the two spectra indicates that the 100-MHz spectrum is greatly expanded over the 60-MHz spectrum. The chemical shift in Hertz for the CH_3 and CH_2 protons is much larger in the 100-MHz spectrum, although the chemical shifts in δ units (ppm) for these protons remain identical to those in the 60-MHz spectrum. Despite the expansion of the spectrum determined at the higher spectrometer frequency, careful examination of the spectra indicates that the coupling constant between the CH_3 and CH_2 protons is 7.5 Hz in both spectra! The spacings of the lines of the triplet and the lines of the quartet do not expand when the spectrum of ethyl iodide is determined at 100 MHz. The extent of coupling between these two sets of protons remains constant irrespective of the spectrometer frequency at which the spectrum was determined. See above figure.

For the interaction of most aliphatic protons in acyclic systems, the magnitudes of coupling constants are always near 7.5 Hz. Compare, for example, 1,1,2-trichloroethane (Fig.), for which J = 6 Hz, and 2-nitropropane (Fig.), for which J = 7 Hz. These coupling constants are typical for the interaction of two hydrogens on adjacent sp^3-hybridized carbon atoms. Two hydrogen atoms on adjacent carbon atoms can be described as a three-bond interaction and abbreviated as ^3J. Typical values for this most commonly observed coupling is approximately 6 to 8 Hz. The bold lines in the diagram show how the hydrogen atoms are three bonds away from each other.

In alkenes, the ^3J coupling constants for hydrogen atoms that are *cis* to each other have values near 10 Hz, while the ^3J coupling constants for hydrogen atoms that are *trans* are larger, 16 Hz. A study of the magnitude of the coupling constant can give important structural information. Following Table gives the approximate values of some representative ^3J coupling constants. Before closing this section, *we should take note of an axiom: the coupling constants of the groups of protons that split one another must be identical* within experimental error.



SOME REPRESENTATIVE ^3J COUPLING CONSTANTS AND THEIR APPROXIMATE VALUES (HZ)

6 to 8	*ortho* 6 to 10	a,a 8 to 14 a,e 0 to 7 e,e 0 to 5
11 to 18	8 to 11	*cis* 6 to 12 *trans* 4 to 8
6 to 15		*cis* 2 to 5 *trans* 1 to 3
4 to 10		5 to 7

Survey of ^{1}H-NMR Spectrum:

We will review the typical ^{1}H-NMR absorptions that may be expected for compounds in each of the most common classes of organic compounds. These guidelines can be consulted whenever you are trying to establish the class of an unknown compound. Coupling behaviors commonly observed in these compounds are also included in the tables. It is included here so that it will be useful if you wish to use this survey later.

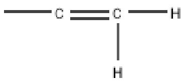
A. Alkanes

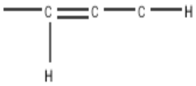
Alkane can have three different types of hydrogens (methyl, methylene, and methine), each of which appears in its own region of the NMR spectrum.

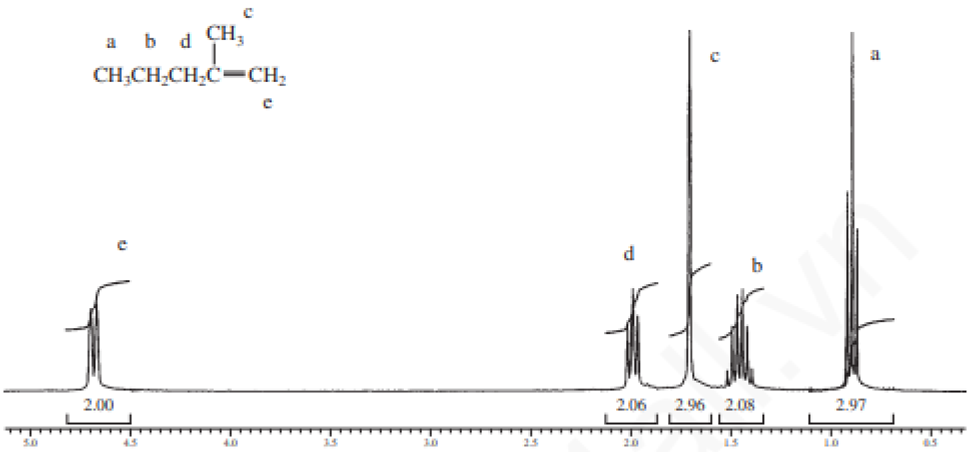
CHEMICAL SHIFTS		
R-CH_3	0.7–1.3 ppm	Methyl groups are often recognizable as a tall singlet, doublet, or triplet even when overlapping other CH absorptions.
R-CH_2-R	1.2–1.4 ppm	In long chains, all of the methylene (CH_2) absorptions may be overlapped in an unresolvable group.
R_3CH	1.4–1.7 ppm	Note that methine hydrogens (CH) have a larger chemical shift than those in methylene or methyl groups.
COUPLING BEHAVIOR		
-CH-CH-	$^{3}J \approx 7–8$ Hz	In hydrocarbon chains, adjacent hydrogens will generally couple, with the spin–spin splitting following the n+1 Rule

B. Alkene

Alkenes have two types of hydrogens: vinyl (those attached directly to the double bond) and allylic hydrogens (those attached to the α carbon, the carbon atom attached to the double bond). Each type has a characteristic chemical shift region.

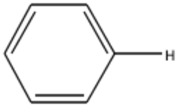
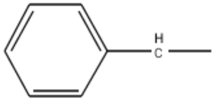
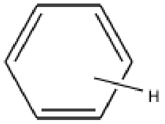
CHEMICAL SHIFTS		
C=C-H	4.5–6.5 ppm	Hydrogens attached to a double bond (vinyl hydrogens) are deshielded by the anisotropy of the adjacent double bond.
C=C-C-H	1.6–2.6 ppm	Hydrogens attached to a carbon adjacent to a double bond (allyic hydrogens) are also deshielded by the anisotropy of the double bond, but because the double bond is more distant, the effect is smaller.
COUPLING BEHAVIOR		
H-C=C-H	$^{3}J_{trans}$=11-18 Hz $^{3}J_{cis}$=6-15 Hz	The splitting patterns of vinyl protons may be complicated by the fact that they may not be equivalent even when located on the same carbon of the double bond
	$^{3}J_{gem}$=0-3 Hz	

	^4J = 0-3 Hz	When allylic hydrogens are present in an alkene, they may show long-range allylic coupling to hydrogens on the far double-bond carbon as well as the usual splitting due to the hydrogen on the adjacent (nearest) carbon.



C. Aromtic Compounds:

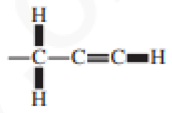
Aromatic compounds have two characteristic types of hydrogens: aromatic ring hydrogens (benzene ring hydrogens) and benzylic hydrogens (those attached to an adjacent carbon atom).

CHEMICAL SHIFTS		
	6.5–8.0 ppm	Hydrogens attached to an aromatic (benzenoid) ring have a large chemical shift, usually near 7.0 ppm. They are deshielded by the large anisotropic field generated by the electrons in the ring’s π system.
	2.3–2.7 ppm	Benzylic hydrogens are also deshielded by the anisotropic field of the ring, but they are more distant from the ring, and the effect is smaller.
COUPLING BEHAVIOR		
	$^3J_{ortho}$≈ 7-10 Hz $^4J_{meta}$ ≈ 2–3 Hz $^5J_{para}$ ≈ 0 - 1 Hz	Splitting patterns for the protons on a benzene ring are discussed. It is often possible to determine the positions of the substituents on the ring from these splitting patterns and the magnitudes of the coupling constants.

D. Alkynes:

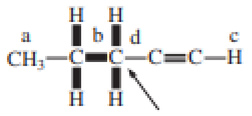
Terminal alkynes (those with a triple bond at the end of a chain) will show an acetylenic hydrogen, as well as the α hydrogens found on carbon atoms next to the triple bond. The acetylenic hydrogen will be absent if the triple bond is in the middle of a chain.

CHEMICAL SHIFTS		
$C\equiv C-CH$	1.7–2.7 ppm	The terminal or acetylenic hydrogen has a chemical shift near 1.9 ppm due to anisotropic shielding by the adjacent π bonds.
$C\equiv C-CH$	1.6–2.6 ppm	Protons on a carbon next to the triple bond are also affected by the π system.
COUPLING BEHAVIOR		
$H-C\equiv C-C-H$	$^4J \approx 2–3$ Hz	"Allylic coupling" is often observed in alkynes, but is relatively small.



$^4J = 2.6$ Hz

There are two H atoms four bonds away, $n = 2 + 1$ = triplet



$^3J = 7$ Hz

There are two H atoms three bonds away, $n = 2 + 1$ = triplet

Proton **d** is split into a triplet by the two neighboring protons (^3J), and then the triplet is split again into doublets (see inset for proton d in Fig.). The type of pattern is referred to as a triplet of doublets. The ^3J coupling constant is calculated by subtraction, for example, counting from left to right, peak 6 from peak 4 (648.3 – 641.3 = 7.0 Hz). The ^4J coupling constant can also be calculated from the triplet of doublets, for example, peak 6 from peak 5 (643.9 – 641.3 = 2.6 Hz).

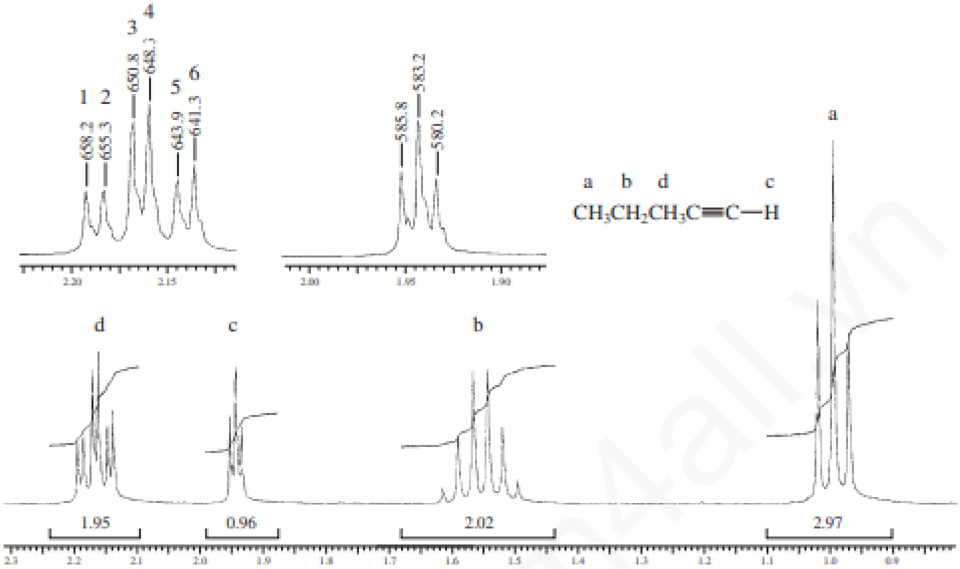
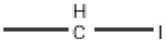


Fig. ^{1}H-NMR spectrum of 1-pentyne

E. **Alkyl Halide**:

In alkyl halide the α hydrogen will be deshielded.

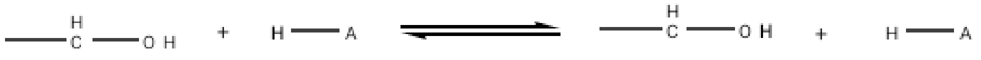
CHEMICAL SHIFTS		
 $-\overset{H}{C}-I$	2.0–4.0 ppm	The chemical shift of a hydrogen atom attached to the same carbon as a halide atom will increase (move further downfield).
 $-\overset{H}{C}-Br$	2.7–4.1 ppm	This deshielding effect is due to the electronegativity of the attached halogen atom. The extent of the shift is increased as the electronegativity of the attached atom increases, with the largest shift found in compounds containing fluorine.
 $-\overset{H}{C}-Cl$	3.1–4.1 ppm	
 $-\overset{H}{C}-F$	4.2–4.8 ppm	
COUPLING BEHAVIOR		
 $-\overset{H}{C}-F$  $-\overset{H}{C}-\overset{F}{C}-$	^2J = 50 Hz ^3J = 20 Hz	Compounds containing fluorine will show spin–spin splitting due to coupling between the fluorine and the hydrogens on either the same or the adjacent carbon atom. ^{19}F has a spin of $\frac{1}{2}$. The other halogens (I, Cl, Br) do not show any coupling.

F. Alcohols:
In alcohols, both the hydroxyl proton and the a hydrogens (those on the same carbon as the hydroxyl group) have characteristic chemical shifts.

CHEMICAL SHIFTS		
C-O-**H**	0.5–5.0 ppm	The chemical shift of the -OH hydrogen is highly variable, its position depending on concentration, solvent, and temperature. The peak may be broadened at its base by the same set of factors.
C**H**-O-**H**	3.2–3.8 ppm	Protons on the α carbon are deshielded by the electronegative oxygen atom and are shifted downfield in the spectrum.
COUPLING BEHAVIOR		
C**H**-O**H**	No coupling (Usually) or $^{3}J = 5$ Hz	Because of the rapid chemical exchange of the -OH proton in many solutions, coupling is not usually observed between the -OH proton and those hydrogens attached to the α carbon.

The chemical shift of the -OH hydrogen is variable, its position depending on concentration, solvent, temperature, and presence of water or of acidic or basic impurities. This peak can be found anywhere in the range of 0.5–5.0 ppm. The variability of this absorption is dependent on the rates of -OH proton exchange and the amount of hydrogen bonding in the solution.

The -OH hydrogen is usually not split by hydrogens on the adjacent carbon (-CH-OH) because rapid exchange decouples this interaction.



No coupling if exchane is rapid

Exchange is promoted by increased temperature, small amounts of acid impurities, and the presence of water in the solution. In ultrapure alcohol samples, -CH-OH coupling is observed. A freshly purified and distilled sample, or a previously unopened commercial bottle, may show this coupling.

On occasion, one may use the rapid exchange of an alcohol as a method for identifying the -OH absorption. In this method, a drop of D_2O is placed in the NMR tube containing the alcohol solution. After shaking the sample and sitting for a few minutes, the -OH hydrogen is replaced by deuterium, causing it to disappear from the spectrum (or to have its intensity reduced).

$$-\overset{H}{C}-OH + D_2O \rightleftharpoons -\overset{H}{C}-OD + HOD$$

deutorium exchane

The hydrogen on the adjacent carbon (-CH-OH) appears in the range 3.2–3.8 ppm, being deshielded by the attached oxygen. If exchange of the O**H** is taking place, this hydrogen will not show any coupling with the -O**H** hydrogen, but will show coupling to any hydrogens on the adjacent carbon located further along the carbon chain. If exchange is not occurring, the pattern of this hydrogen may be complicated by differently sized coupling constants for the –C**H**-O**H** and –C**H**-C**H**-O- couplings.

A spectrum of 2-methyl-1-propanol is shown in Figure. Note the large downfield shift (3.4 ppm) of the hydrogens attached to the same carbon as the oxygen of the hydroxyl group. The hydroxyl group appears at 2.4 ppm, and in this sample it shows some coupling to the hydrogens on the adjacent carbon. The methine proton at 1.75 ppm has been expanded and inset on the spectrum. There are nine peaks (nonet) in that pattern, suggesting coupling with the two methyl groups and one methylene group, n = (3 + 3 + 2) + 1 = 9.

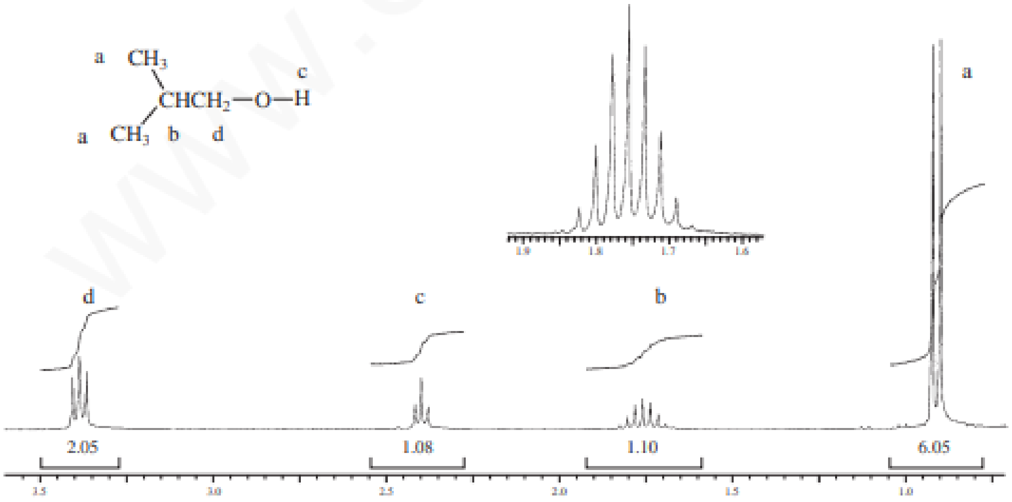


FIGURE: 1 H NMR spectrum of 2-methyl-1-propanol.

G. Ethers:

In ethers, the a hydrogens (those attached to the a carbon, which is the carbon atom attached to the oxygen) are highly deshielded.

CHEMICAL SHIFTS		
R-O-C**H**	3.2–3.8 ppm	The hydrogens on the carbon attached to the oxygen are deshielded due to the electronegativity of the oxygen.

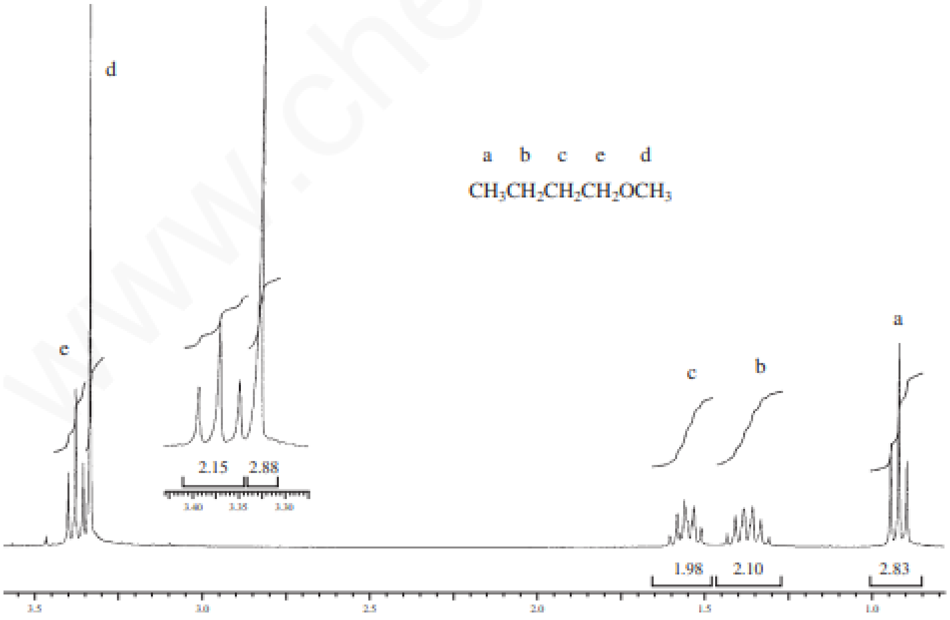
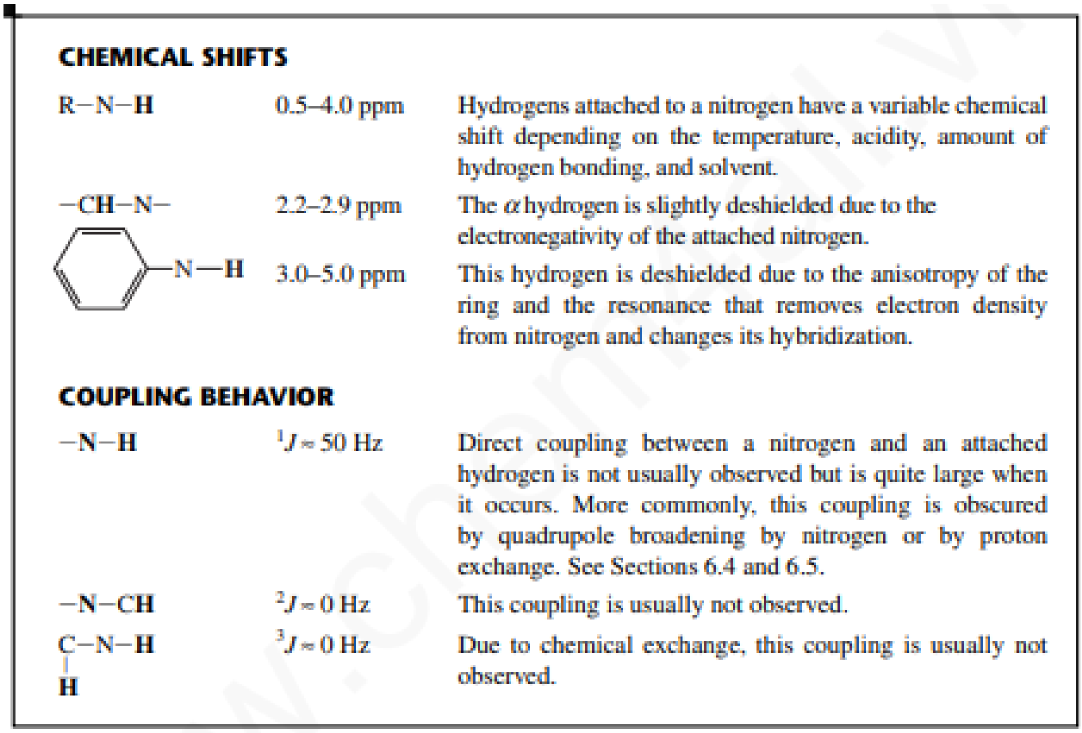


FIGURE: 1 H-NMR spectrum of butyl methyl ether

H. Amines:

Two characteristic types of hydrogens are found in amines: those attached to nitrogen (the hydrogens of the amino group) and those attached to the a carbon (the same carbon to which the amino group is attached)



CHEMICAL SHIFTS

R—N—**H**	0.5–4.0 ppm	Hydrogens attached to a nitrogen have a variable chemical shift depending on the temperature, acidity, amount of hydrogen bonding, and solvent.
—C**H**—N—	2.2–2.9 ppm	The α hydrogen is slightly deshielded due to the electronegativity of the attached nitrogen.
—N—**H**	3.0–5.0 ppm	This hydrogen is deshielded due to the anisotropy of the ring and the resonance that removes electron density from nitrogen and changes its hybridization.

COUPLING BEHAVIOR

—N—**H**	$^1J \approx 50$ Hz	Direct coupling between a nitrogen and an attached hydrogen is not usually observed but is quite large when it occurs. More commonly, this coupling is obscured by quadrupole broadening by nitrogen or by proton exchange. See Sections 6.4 and 6.5.
—N—C**H**	$^2J \approx 0$ Hz	This coupling is usually not observed.
C—N—**H** **H**	$^3J \approx 0$ Hz	Due to chemical exchange, this coupling is usually not observed.

I. Nitriles:

In Nitriles, only the α hydrogens (those attached to the same carbon as the cyano group) have a characteristic chemical shift.

CHEMICAL SHIFTS		
-C**H**-CN	2.1–3.0 ppm	The a hydrogens are slightly deshielded by the cyano group.

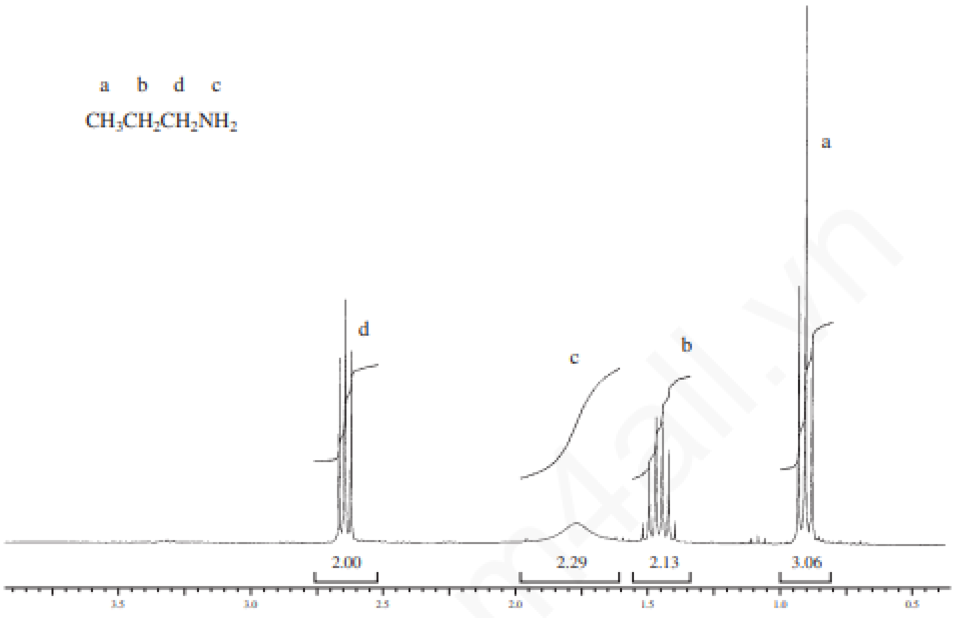


Fig.: 1H-NMR spectrum of propylamine

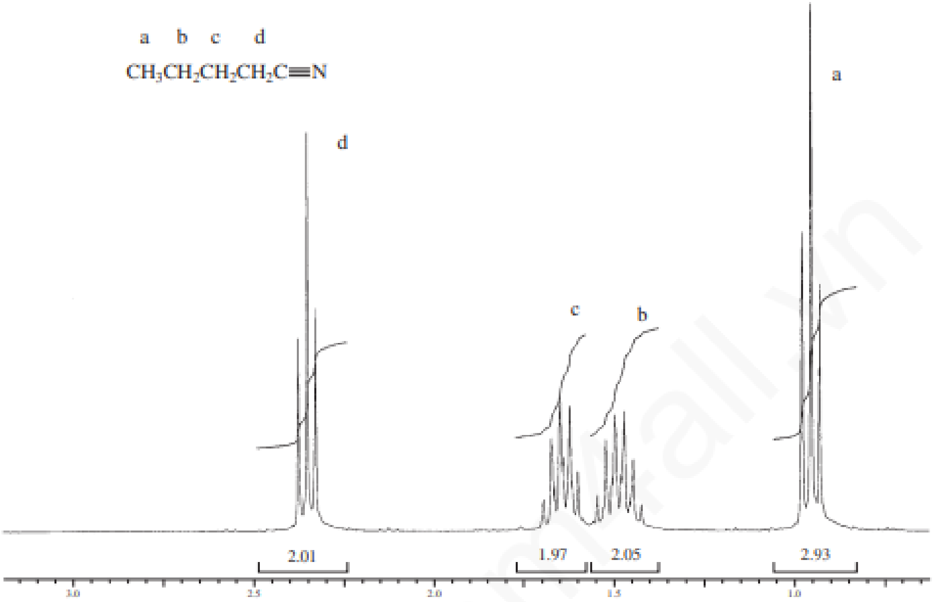


Fig.: 1H-NMR spectrum of valeronitrile (propane nitrile)

J. Aldehydes:

Two types of hydrogens are found in aldehydes: the aldehyde hydrogen and the a hydrogens (those hydrogens attached to the same carbon as the aldehyde group).

CHEMICAL SHIFTS

R-C**H**O	9.0–10.0 ppm	The aldehyde hydrogen is shifted far downfield due to the anisotropy of the carbonyl group (C=O).
R-C**H**-CH=O	2.1–2.4 ppm	Hydrogens on the carbon adjacent to the C=O group are also deshielded due to the carbonyl group, but they are more distant, and the effect is smaller.
COUPLING BEHAVIOR		
-C**H**-C**H**O	^3J = 1-3 Hz	Coupling occurs between the aldehyde hydrogen and hydrogens on the adjacent carbon, but 3 J is small.

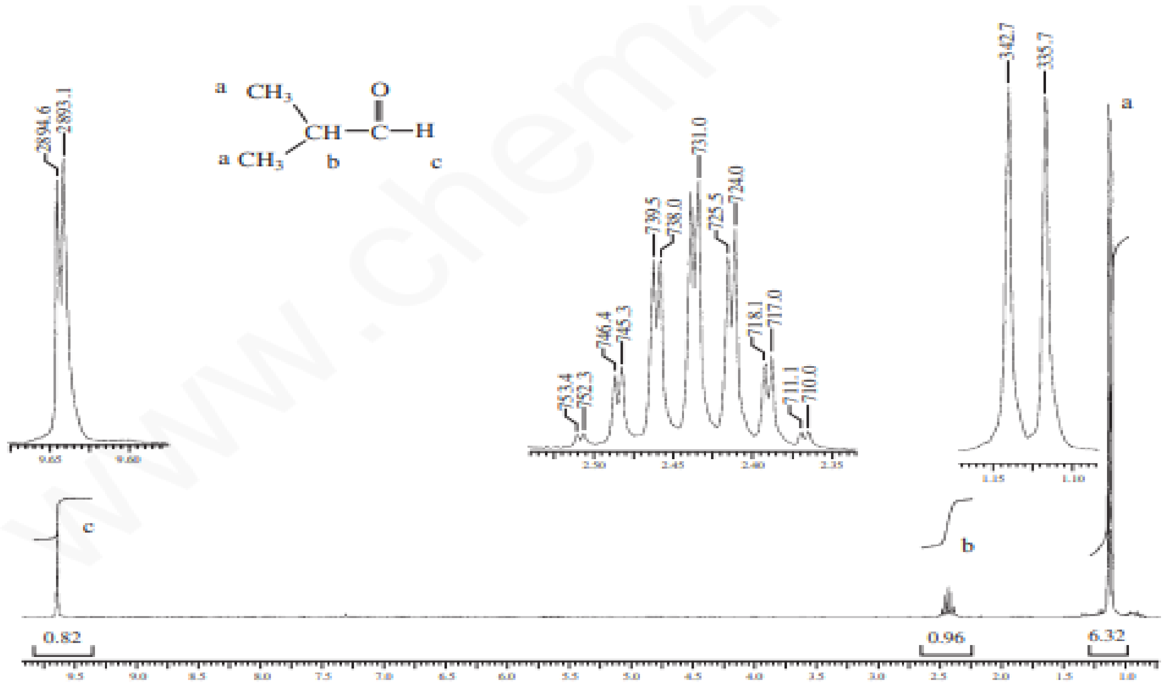


FIGURE: 1H-NMR spectrum of 2-methylpropanal (isobutyraldehyde).

K. Ketones:

Ketones have only one distinct type of hydrogen atom—those attached to the α carbon.

CHEMICAL SHIFTS		
R-C**H**-CR=O	2.1–2.4 ppm	The α hydrogens in ketones are deshielded by the anisotropy of the adjacent C=O group.

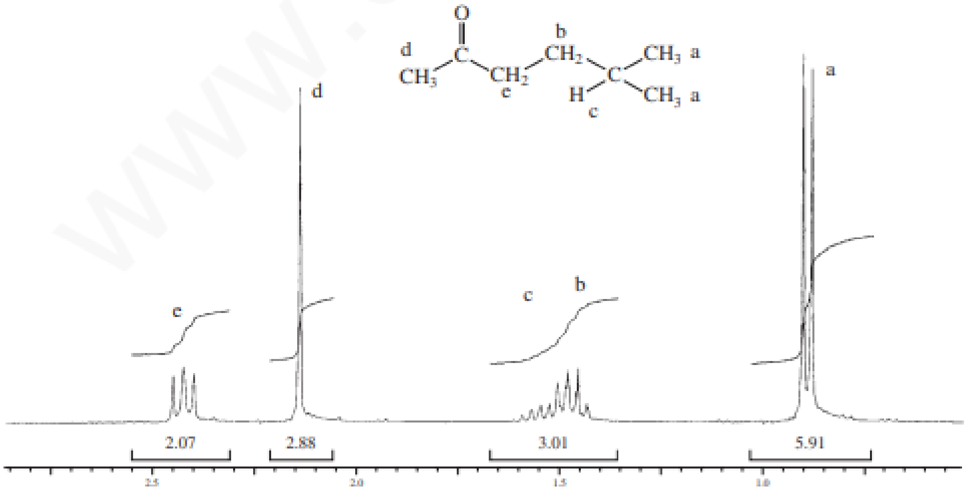
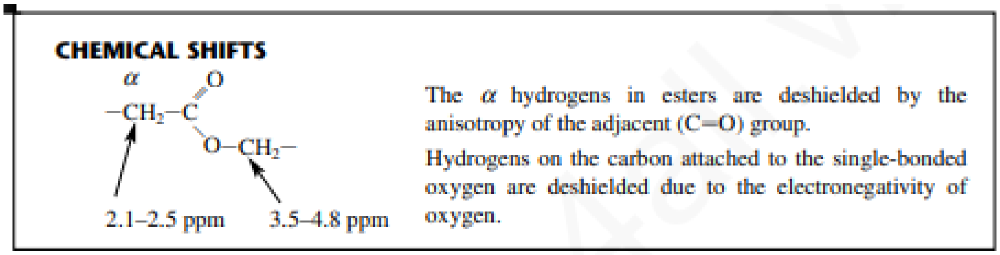


FIGURE: 1 H-NMR spectrum of 5-methyl-2-hexanone

L. Esters:

Two distinct types of hydrogen are found in esters: those on the carbon atom attached to the oxygen atom in the alcohol part of the ester and those on the α carbon in the acid part of the ester (that is, those attached to the carbon next to the C=O group).



CHEMICAL SHIFTS

2.1–2.5 ppm

3.5–4.8 ppm

The α hydrogens in esters are deshielded by the anisotropy of the adjacent (C=O) group.

Hydrogens on the carbon attached to the single-bonded oxygen are deshielded due to the electronegativity of oxygen.

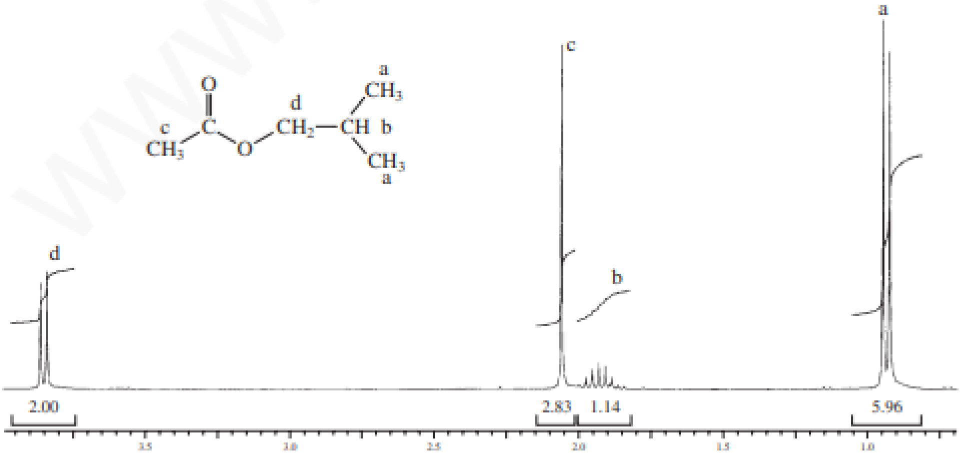
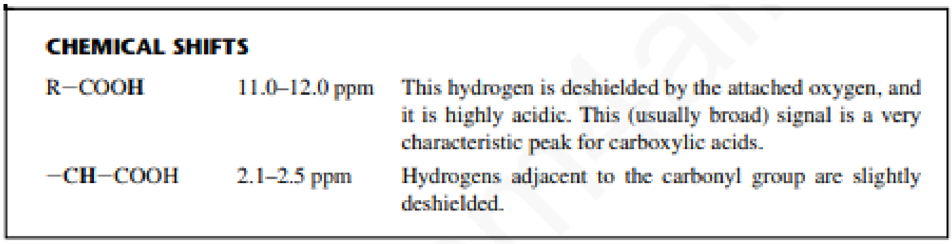


FIGURE: 1 H-NMR spectrum of isobutyl acetate.

M. Carboxylic Acids:

Carboxylic acids have the acid proton (the one attached to the -COOH group) and the α hydrogens (those attached to the same carbon as the carboxyl group).



CHEMICAL SHIFTS

R−COOH	11.0–12.0 ppm	This hydrogen is deshielded by the attached oxygen, and it is highly acidic. This (usually broad) signal is a very characteristic peak for carboxylic acids.
−CH−COOH	2.1–2.5 ppm	Hydrogens adjacent to the carbonyl group are slightly deshielded.

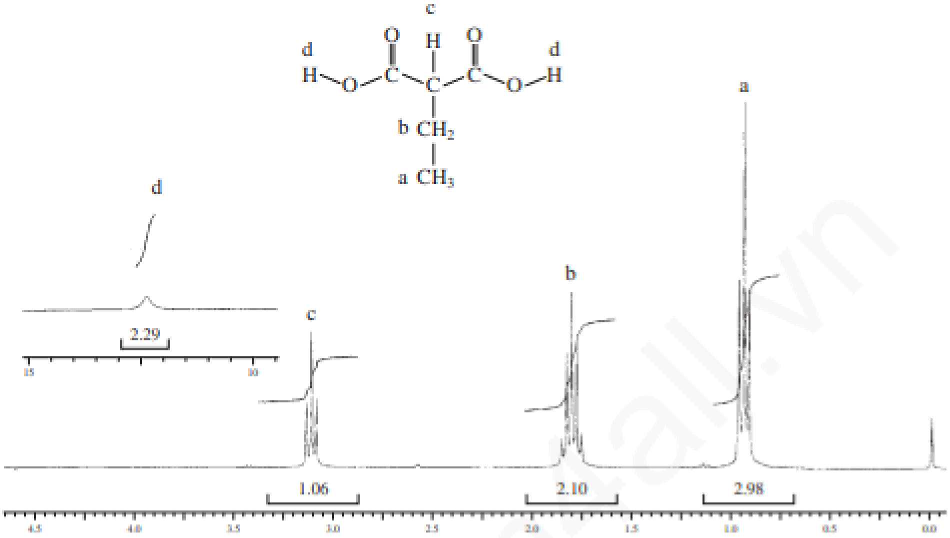


Fig.: 1H-NMR spectrum of ethylmalonic acid.

N. Amides:

Amides have three distinct types of hydrogens: those attached to nitrogen, a hydrogens attached to the carbon atom on the carbonyl side of the amide group, and hydrogens attached to a carbon atom that is also attached to the nitrogen atom,

The -NH absorptions of an amide group are highly variable, depending not only on their environment in the molecule, but also on temperature and the solvent used. Because of resonance between the unshared pairs on nitrogen and the carbonyl group, rotation is restricted in most amides. Without rotational freedom, the two hydrogens attached to the nitrogen in an unsubstituted amide are not equivalent, and **two different absorption peaks** will be observed, one for each hydrogen. Nitrogen atoms also have a quadrupole moment, its magnitude depending on the particular molecular environment. If the nitrogen atom has a large quadrupole moment, the attached hydrogens will show peak broadening (a widening of the peak at its base) and an overall reduction of its intensity. Hydrogens adjacent to a carbonyl group (regardless of type) all absorb in the same region of the NMR spectrum: 2.1–2.5 ppm.

The spectrum of butyramide is shown in Figure. Notice the separate absorptions for the two -NH hydrogens (6.6 and 7.2 ppm). This occurs due to restricted rotation in this compound.

CHEMICAL SHIFTS		
R(CO)-N-**H**	5.0–9.0 ppm	Hydrogens attached to an amide nitrogen are variable in chemical shift, the value being dependent on the temperature, concentration, and solvent.
-C**H**-CONH-	2.1–2.5 ppm	The a hydrogens in amides absorb in the same range as other acyl (next to C=O) hydrogens. They are slightly deshielded by the carbonyl group.
R(CO)-N-C**H**	2.2–2.9 ppm	Hydrogens on the carbon next to the nitrogen of an amide are slightly deshielded by the electronegativity of the attached nitrogen.
COUPLING BEHAVIOR		
-**N**-**H**	^1J = 50 Hz	In cases in which this coupling is seen (rare), it is quite large, typically 50 Hz or more. In most cases, either the quadrupole moment of the nitrogen atom or chemical exchange decouples this interaction.
-**N**-C**H**-	^2J = 0 Hz	Usually not seen for the same reasons stated above.
-N**H**-C**H**-	^3J = 0-7 Hz	Exchange of the amide NH is slower than in amines, and splitting of the adjacent C**H** is observed even if the N**H** is broadened

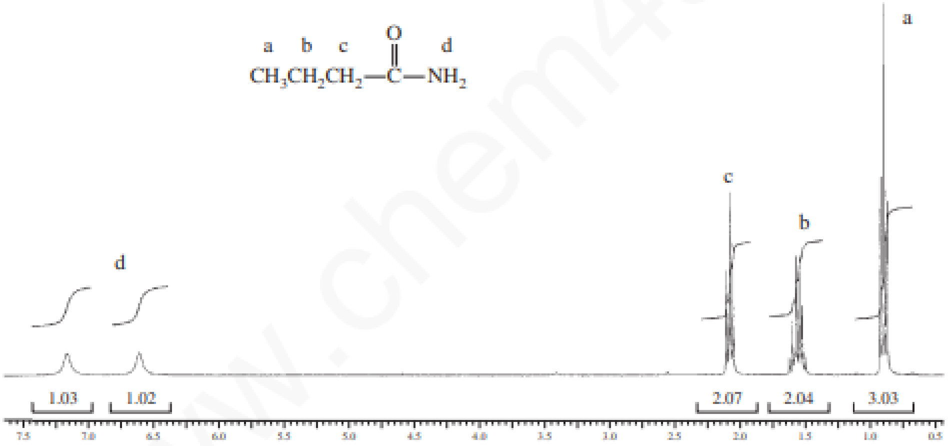


FIGURE: 1H-NMR spectrum of butyramide.

O. Nitroalkanes

In nitroalkanes, *α* hydrogens, those hydrogen atoms that are attached to the same carbon atom to which the nitro group is attached, have a characteristically large chemical shift.

SPECTRAL ANALYSIS BOX—Nitroalkanes

$-\mathbf{CH}-NO_2$	4.1–4.4 ppm	Deshielded by the nitro group.

Hydrogens on a carbon next to a nitro group are highly deshielded and appear in the range 4.1–4.4 ppm. The electronegativity of the attached nitrogen and the positive formal charge assigned to that nitrogen clearly indicate the deshielding nature of this group.

A spectrum of 1-nitrobutane is shown in Figure. Note the large chemical shift (4.4 ppm) of the hydrogens on the carbon adjacent to the nitro group.

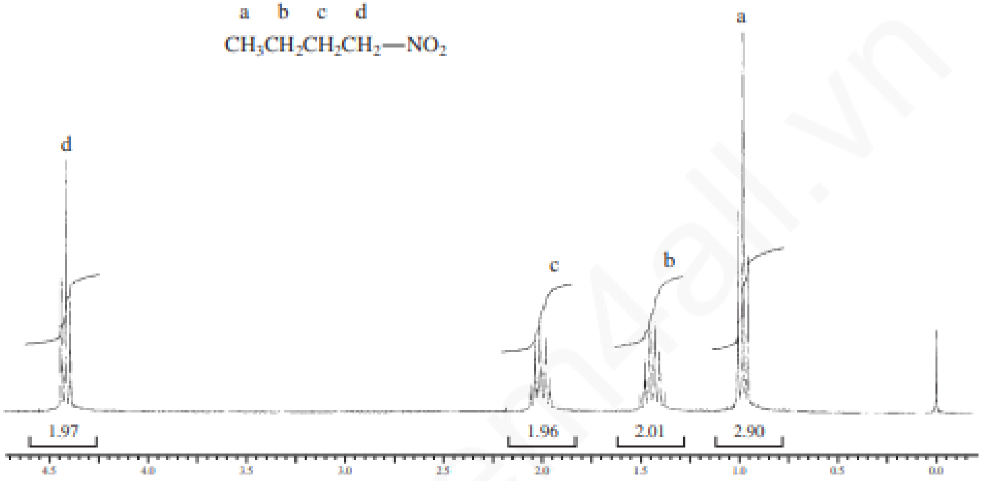
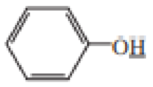


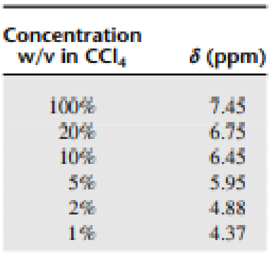
FIGURE: 1H-NMR spectrum of 1-nitrobutane.

PROBLEMS:

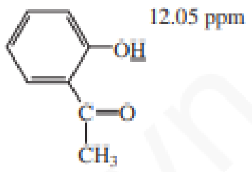
1. What are the allowed nuclear spin states for the following atoms?
   (a) ^{14}N (b) ^{13}C (c) ^{17}O (d) ^{19}F
2. Calculate the chemical shift in parts per million (δ) for a proton that has resonance 128 Hz downfield from TMS on a spectrometer that operates at 60 MHz.
3. A proton has resonance 90 Hz downfield from TMS when the field strength is 1.41 Tesla (14,100 Gauss) and the oscillator frequency is 60 MHz.
   (a) What will be its shift in Hertz if the field strength is increased to 2.82 Tesla and the oscillator frequency to 120 MHz?
   (b) What will be its chemical shift in parts per million (δ)?
4. Acetonitrile (CH_3CN) has resonance at 1.97 ppm, whereas methyl chloride (CH_3Cl) has resonance at 3.05 ppm, even though the dipole moment of acetonitrile is 3.92 D and that of methyl chloride is only 1.85 D. The larger dipole moment for the cyano group suggests that the electronegativity of this group is greater than that of the chlorine atom. Explain why the methyl hydrogens on acetonitrile are actually more shielded than those in methyl chloride, in contrast with the results expected on the basis of electronegativity. (Hint: What kind of spatial pattern would you expect for the magnetic anisotropy of the cyano group, CN?)
5. The position of the OH resonance of phenol varies with concentration in solution, as the following table shows. On the other hand, the hydroxyl proton of ortho-hydroxyacetophenone appears at 12.05 ppm and does not show any great shift upon dilution. Explain.



Phenol

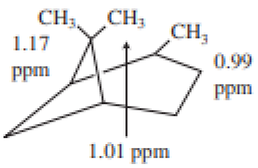


Concentration w/v in CCl_4	δ (ppm)
100%	7.45
20%	6.75
10%	6.45
5%	5.95
2%	4.88
1%	4.37

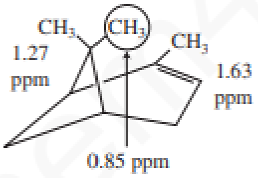


o-Hydroxyacetophenone

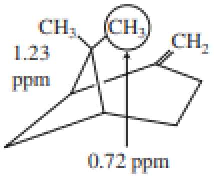
6. The chemical shifts of the methyl groups of three related molecules, pinane, α-pinene, and β-pinene, follow.



Pinane



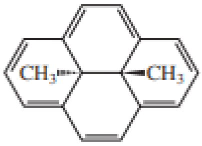
α-Pinene



β-Pinene

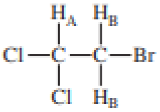
Build models of these three compounds and then explain why the two circled methyl groups have such small chemical shifts.

7. In benzaldehyde, two of the ring protons have resonance at 7.87 ppm, and the other three have resonance in the range from 7.5 to 7.6 ppm. Explain.
8. Make a three-dimensional drawing illustrating the magnetic anisotropy in 15,16-dihydro-15,16-dimethylpyrene, and explain why the methyl groups are observed at −4.2 ppm in the ^{1}H NMR spectrum.



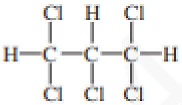
15,16-Dihydro-15,16-dimethylpyrene

9. Work out the spin arrangements and splitting patterns for the following spin system:



$\mathrm{Cl{-}C(H_A)(Cl){-}C(H_B)(H_B){-}Br}$

10. Explain the patterns and intensities of the isopropyl group in isopropyl iodide.
11. What spectrum would you expect for the following molecule?



$\mathrm{H{-}C(Cl)(Cl){-}C(H)(Cl){-}C(Cl)(Cl){-}H}$

12. What arrangement of protons would give two triplets of equal area?
13. Predict the appearance of the NMR spectrum of propyl bromide.

References:

1. Spectroscopy by Pavia, Lampman, Kriz and Vyvyan
2. Organic Spectroscopy, principal and application by Jag Mohan