

Chapter 11: Nuclear Magnetic Resonance Spectroscopy (NMR)

NMR → one of the

most important techniques for characterizing organic compounds

How does NMR work?

→ A magnetic field is applied and used to create states in the molecule that differ in energy (ΔE). Then the energy difference between these states is measured to generate an NMR

Theory behind NMR

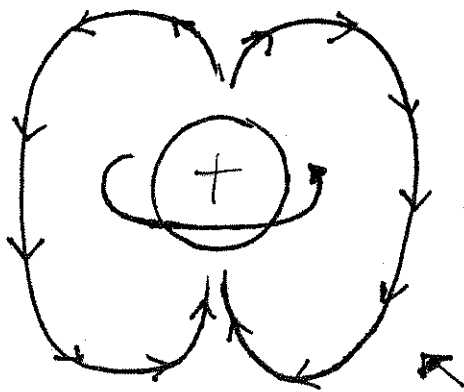
→ helps us understand how NMR works

Nuclear spin: a nucleus with an odd mass number has a nuclear spin that can be detected by NMR

(also, even mass number and odd atomic #) ex: ^{14}N

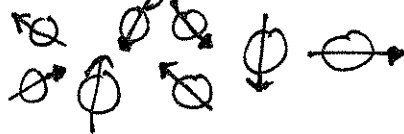
Ex: a proton (H^+)

- positively charged nucleus
- behaves as if it were spinning on an axis
- with moving charge (+ or -) will generate a magnetic field



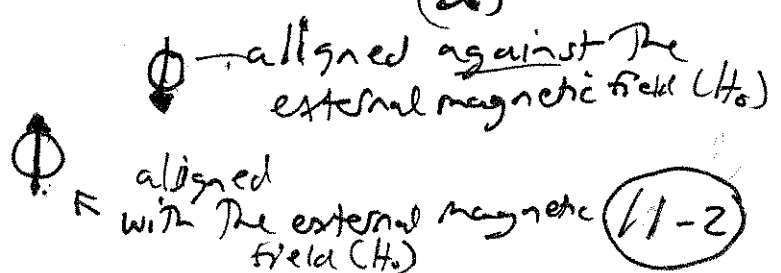
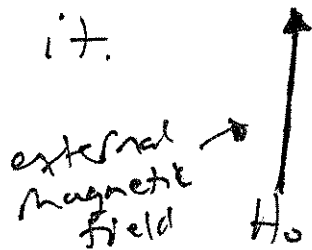
- behaves as a small magnet
- has a magnetic moment
describes the direction of the magnetic field that is generated

- In the absence of an applied magnetic field these magnetic moments are randomly oriented.



- In an external magnetic field: magnetic moments of the nuclei align with the field or against it.

(β)

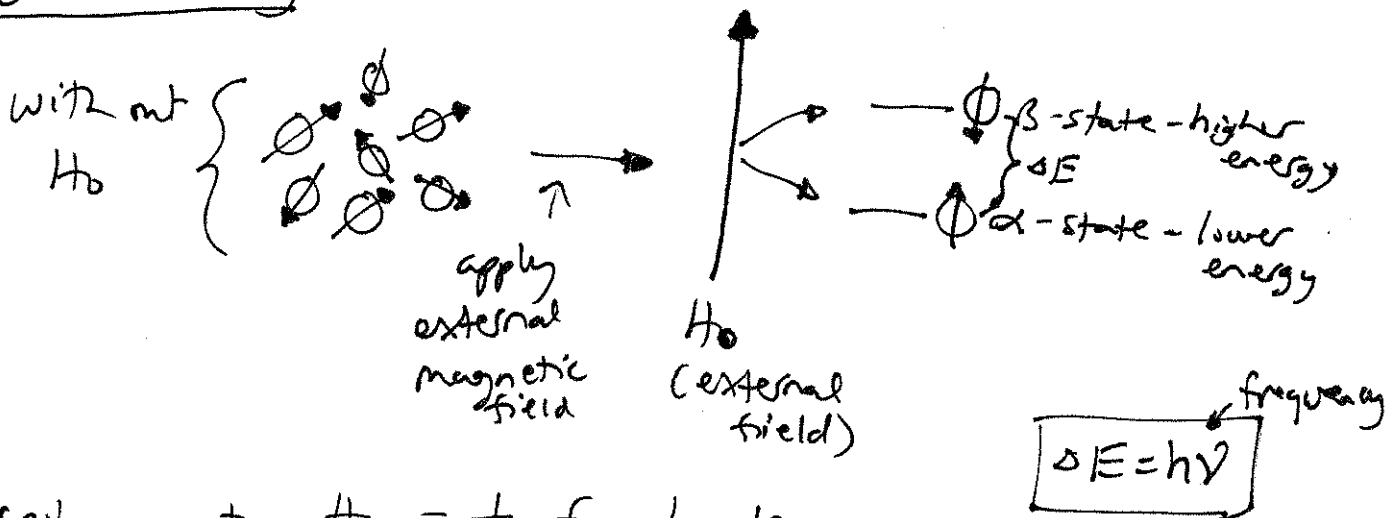


Compare - a compass needle points towards North (aligns with earth's magnetic field)

Applied Field = H_0

Alignment against $H_0 = (\beta)$ - higher energy state than alignment with the field (α) (but only a very small difference)
energy

Diagrammatically:



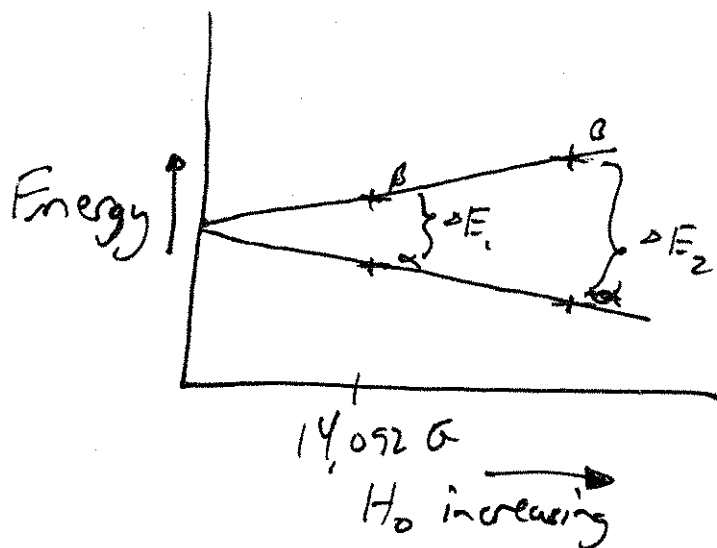
- spin quantum # = $\frac{1}{2}$ for hydrogen
- Add radiation of the proper frequency ^(radio waves) → nucleus of $+\frac{1}{2}$ spin can absorb a quantum of light and be converted to a higher energy spin state (termed "spin flipping")

At higher magnetic fields:

1) More spins will be in the α -spin state AND

2) The energy difference between the α & β spin states is larger

(Therefore need more energy to "flip" the spins in higher magnetic fields)



• The amount of energy required to "flip" the spins is very small

→ For a H_0 of 14,092 G
 $\Delta E_1 = 0.0057 \frac{\text{cal}}{\text{mole}}$ (between α & β spin state of H^+) (Gauss)

• The energy difference of $\Delta E_1 = 0.0057 \frac{\text{cal}}{\text{mole}}$ corresponds to light of a frequency of 60,000,000 Hz or 60 MHz ← in radiowave range of the electromagnetic radiation spectrum
cycles per second

• If we increase the external magnetic field strength, need higher frequency radiation to flip spins.

Chemical Shift

- Now that we've considered how an isolated proton (H^+) behaves in a magnetic field, let's consider how a proton in a molecule behaves

H^+ - a bare nucleus, no electrons in its valence shell

H in molecule - surrounded by electron clouds of their bonding electrons
- electrons circulate and generate their own magnetic field. Their magnetic field is opposite to that of the applied field (H_0)

Result: The nucleus of the hydrogen experiences a magnetic field that is lower than the applied field (H_0)

• called Diamagnetic Shielding

$$\textcircled{H} = H_0 - H' \leftarrow \begin{array}{l} \text{from electron's} \\ \text{magnetic} \\ \text{field} \end{array}$$

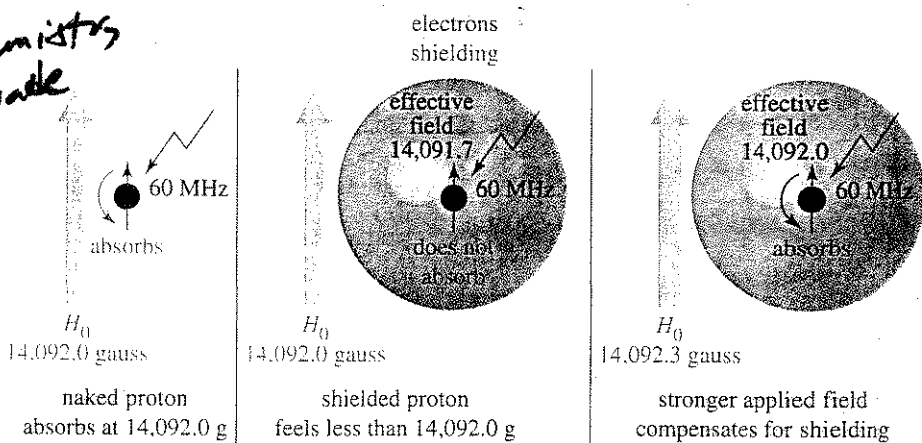
magnetic field at nucleus applied field

- Protons in different electronic environments will experience different amounts of shielding so different amounts of energy is required to flip the spins

→ This gives rise to different chemical shifts

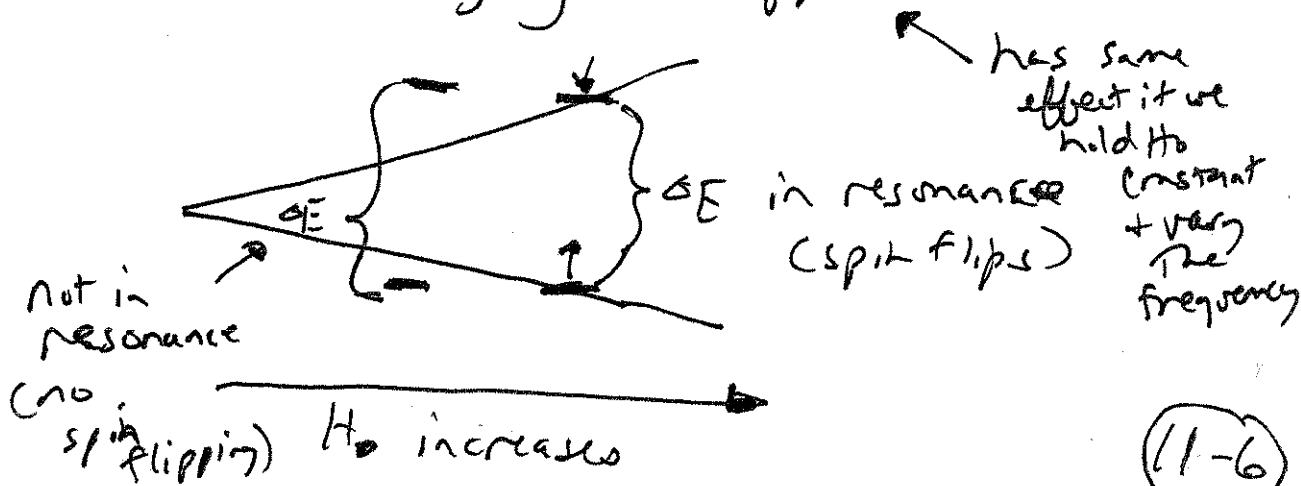
From Organic Chemistry by L.G. Wade

FIGURE 12-5 The magnetic field must be increased slightly above 14,092 gauss (at 60 MHz) for resonance of a shielded proton.

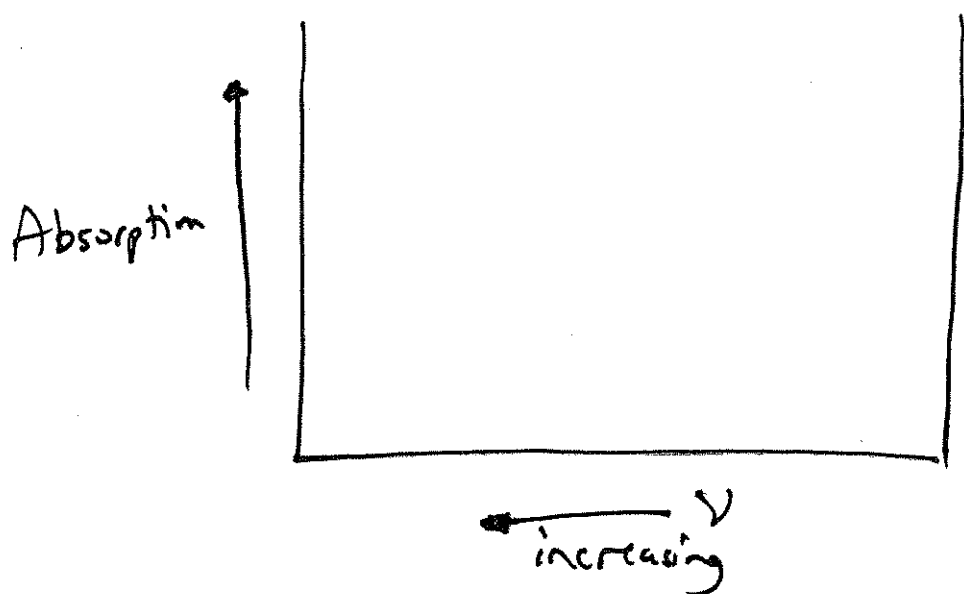


NMR spectrometer measures the amount of energy necessary to cause spin flipping

→ It works by holding frequency constant (ex 60 MHz) + varying the applied field (H_0)



- When each proton reaches its resonance, energy is absorbed from the radio waves causing the spins to flip \rightarrow This absorption of energy is measured and recorded as an NMR spectrum



$$\Delta E = h\nu$$

$$s.o. \nu = \frac{\Delta E}{h}$$

$\Delta E \propto \nu$

↑
proportional

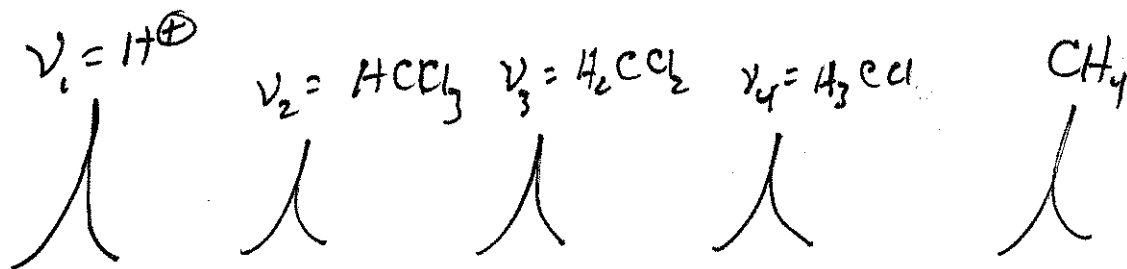
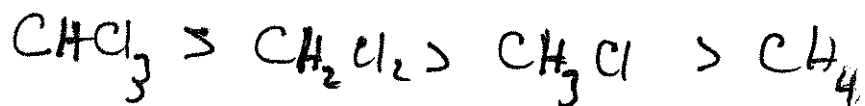
1) H^{\oplus} - not shielded - experiences full applied field and absorbs radiation of high ν

2) $H \rightarrow \begin{array}{c} \nearrow Cl \\ C \\ \searrow Cl \\ \downarrow Cl \end{array}$ - strongly polarized, but H is still more shielded than H^{\oplus} , so doesn't experience full H_0

(experienced field less, so ΔE less & ν less) (11-7)

3) add more electron density to the C-H bond →
 H will resonate at an even lower ν (more shielded)

ex



← ν (frequency)
 (for spin flipping)

(parts per million)

In NMR actually plot Absorbance vs PPM (not ν)

$$\text{ppm} = \delta = \frac{\nu_{\text{obs}} - \nu_{\text{std}}}{\nu_0} \times 10^6 = \frac{\Delta\nu}{\nu_0} \times 10^6$$

where ν_{obs} = resonance frequency observed

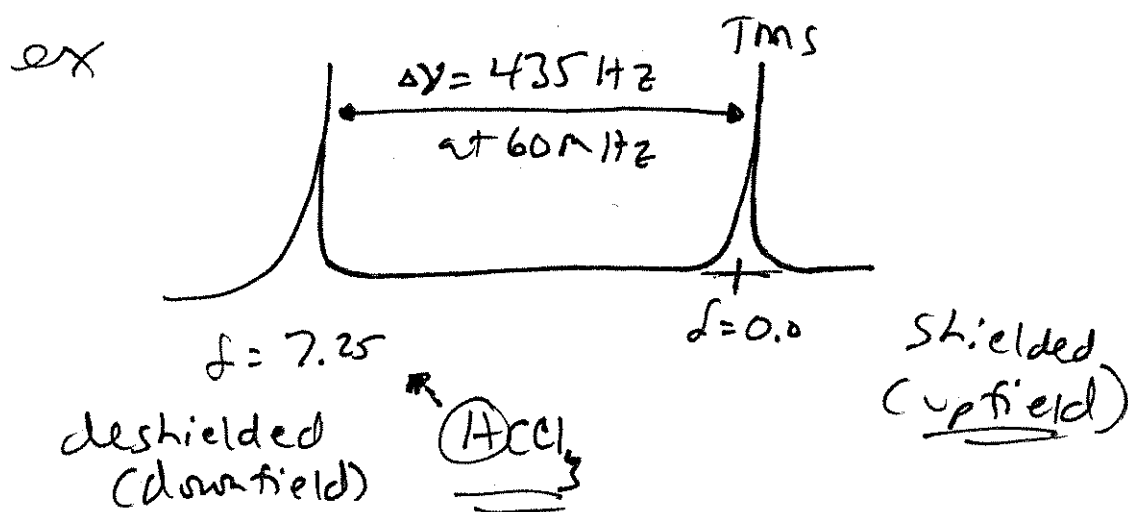
ν_{std} = resonance frequency of internal std

ν_0 = operating frequency of the instrument

(tetramethylsilane)
Internal standard - use $\text{Me}_4\text{Si} = \text{TMS } (\text{CH}_3)_4\text{Si}$

→ in TMS the H's are very shielded
because of e^- donation from silicon
(Carbon more electronegative than Si)

→ put TMS in with sample and manually
adjust its resonance to 0.00 ppm



$$\delta_{\text{CHCl}_3} = \frac{435}{60,000,000} \times 10^6 = \frac{435 \times 10^6}{60 \times 10^6} = \frac{435}{60} = 7.25 \text{ ppm}$$

Why do we use ppm? Because we can directly

compare results obtained from spectrometers
operating at different frequencies

Note: useful to know → The APPROXIMATE shifts of hydrogens in commonly encountered functional groups

Table 10.3 (p 361 in text)

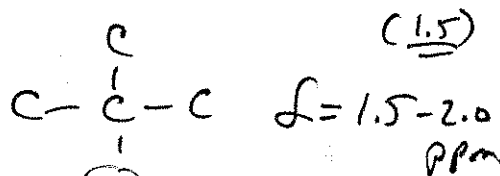


Table 10.3 Typical Chemical Shifts for Types of Hydrogen Atoms Seen in Proton Magnetic Resonance Spectra

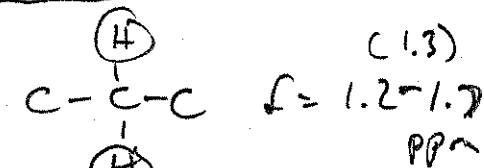
Type of Hydrogen Atom	δ^*	Type of Hydrogen Atom	δ^*	Type of Hydrogen Atom	δ^*
RCH_3	0.9-1.0	$RNHCH_3$	2-3	RNH_2	1-3
RCH_2R	1.2-1.7	RCH_2X (X=Cl, Br, I)	2.6-4.3	$ArNH_2$	3-5
R_3CH	1.5-2.0	$ROCH_3, RCOCH_3$	3.8	$RCNHR$	5-9
$R_2C=CCH_3$ R'	1.5-1.8	$RCH=CH_2$	3.8-6.5	ROH	1-5
$RC(=O)CH_3$	2.0-2.3	ArH	6.0-8.8	$ArOH$	4-7
$ArCH_3$	2.3	$RCHO$	9.5-10	$RCOOH$	10-13
$RC\equiv CH$	2.3-3.0				

* The chemical shift values are given in parts per million (ppm) relative to tetramethylsilane at δ 0.00 and are for the hydrogen atoms shown in boldface in the formulas. The values for hydrogen atoms on oxygen and nitrogen are highly dependent on solvent, concentration, and temperature.

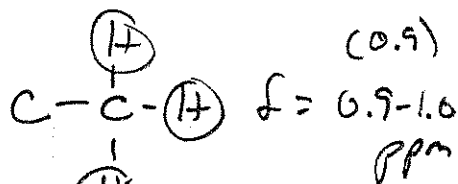
alkanes



methine



methylene



trimethyl

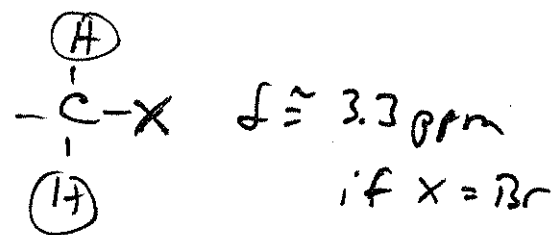
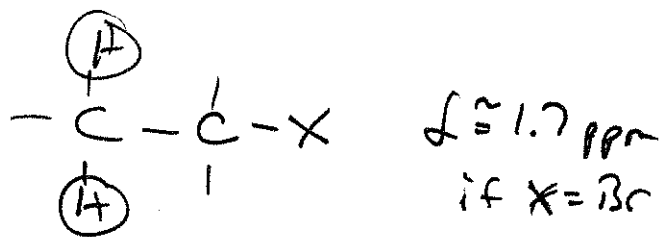
Table 10.2 (p 358 in text)

Table 10.2 Chemical Shifts for Carbon Atoms in ^{13}C Nuclear Magnetic Resonance Spectra

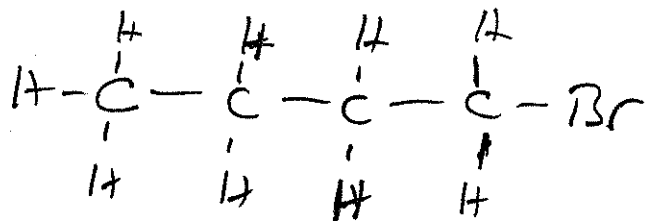
Type of Carbon Atom	δ^*	Type of Carbon Atom	δ^*
RCH_2CH_3	13-16	$RCH=CH_2$	115-120
RCH_2CH_2	16-25	$RCH=CH_2$	125-140
R_3CH	25-38	$RC\equiv N$	117-125
CH_3CR	-30	ArH	125-150
CH_2COR	-20	$RCOR'$	170-175
RCH_2Cl	40-45	$RCOOH$	177-185
RCH_2Br	28-35	$RCHO$	190-200
RCH_2NH_2	37-45	RCR'	205-220
RCH_2OH	50-64		
$RC\equiv CH$	67-70		
$RC\equiv CH$	74-85		

* The chemical shift values are given in parts per million (ppm) relative to tetramethylsilane at δ 0.00 and are for the carbon atoms shown in boldface in the formulas.

(11-10)



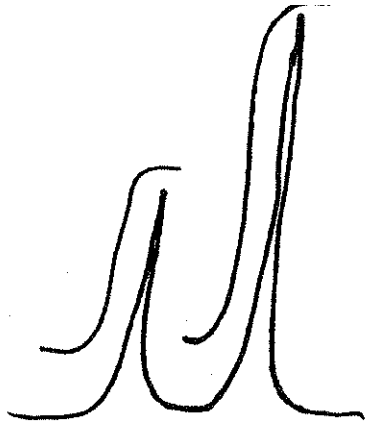
- With this data we can assign approximate chemical shifts to the molecule below



Integration

→ hydrogens in different ^{electronic} environments give rise to signals in different regions of the NMR spectrum.

- # of signals - tells us how many kinds of protons there are in a molecule.
- measure the area of each signal - determines the relative # of different kinds of hydrogen.



ratio 1 : 2

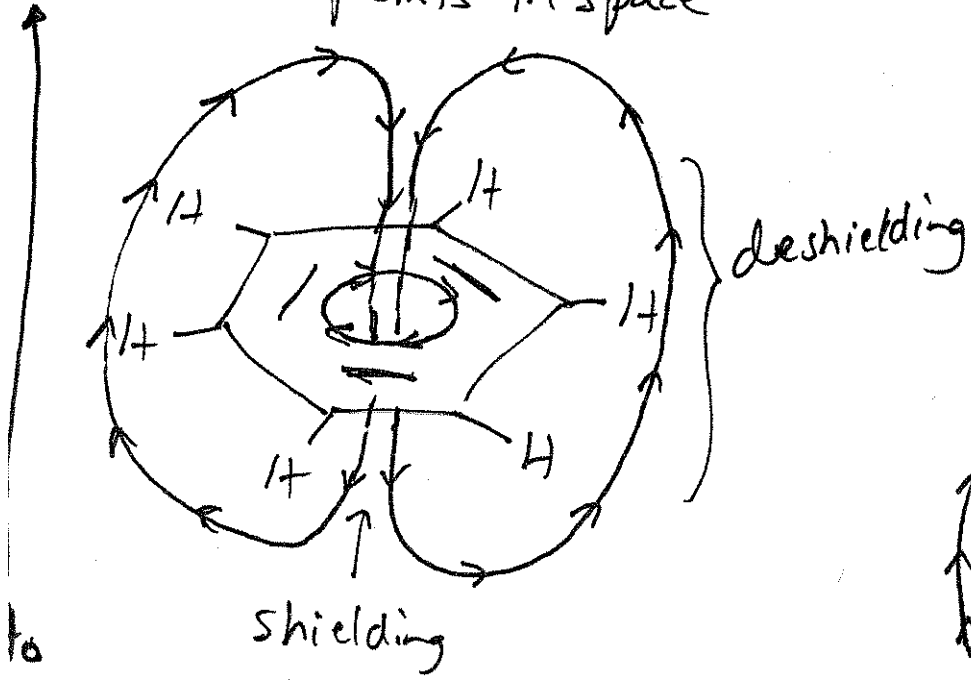
Could be: 1 + 2 protons
 2 + 4 protons
 3 + 6 protons etc

- Most spectrometers integrate the area under the peak to give relative areas directly.
- The amount of energy absorbed at each resonance frequency is directly proportional to the # of nuclei that are absorbing the energy.

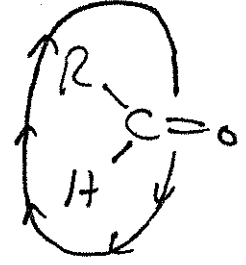
Compounds with π -bonds

Magnetic Anisotropy

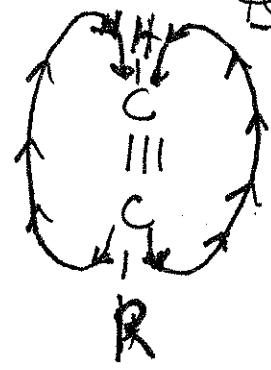
→ difference in magnetic properties at different points in space



aldehydes - deshielded



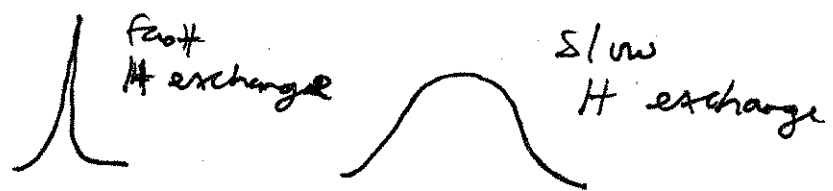
terminal alkynes
more shielded



Hydrogen atoms on hydroxyl groups -O-H =

→ location of -O-H hydrogen can vary a lot because of ability of these groups to hydrogen bond

- Chemical shift of O-H hydrogens depend on:
 - Concentration
 - NMR solvent (polar protic, polar aprotic, nonpolar)
- can be sharp or broad signals



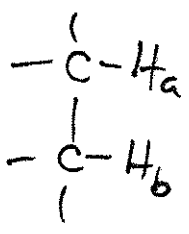
- may or may not be split by adjacent hydrogens

Spin-Spin Splitting (Coupling)

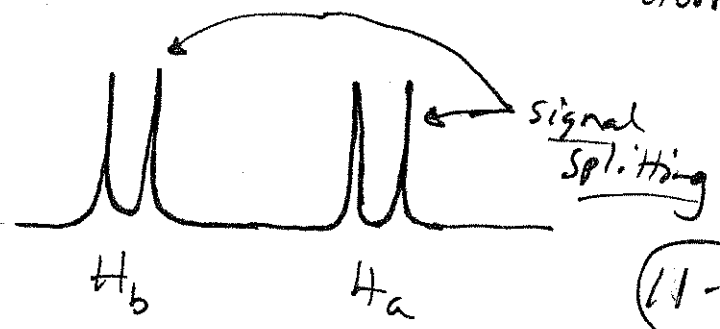
- Chemical shift of a proton: depends on its electronic environment

Splitting - depends on the neighboring protons

→ Consider 2 protons ($H_a + H_b$) attached to neighboring atoms



If H_b is deshielded relative to H_a you observe (usually)

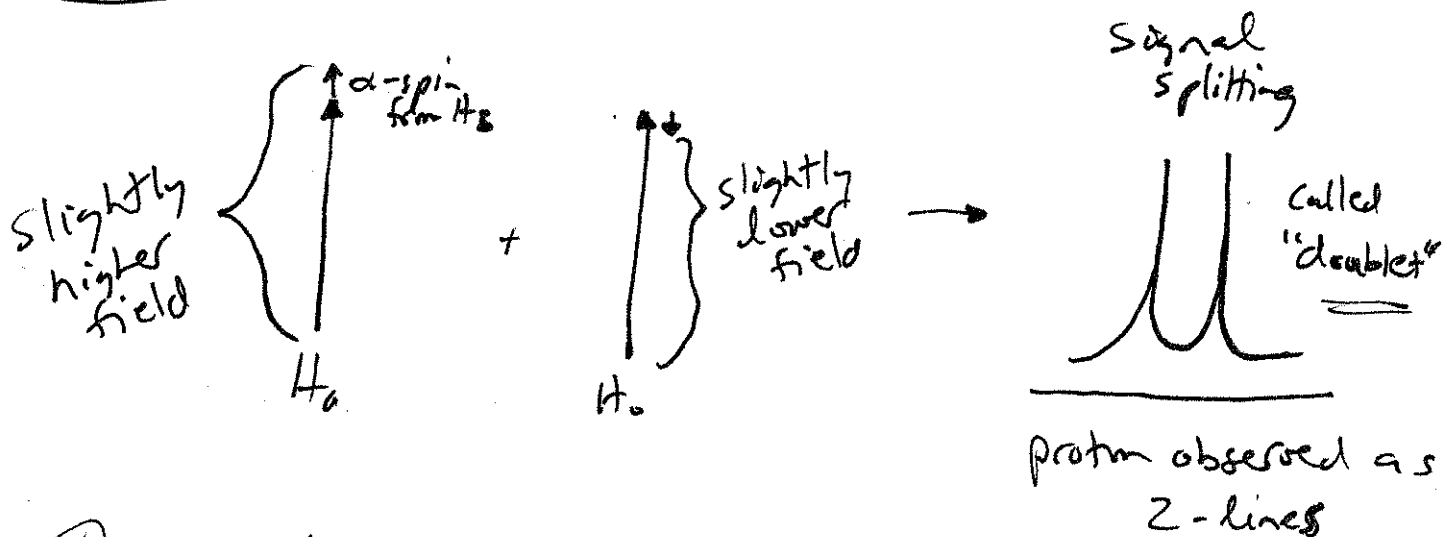


Why do we observe signal splitting?

Because the presence of a nearby proton (H_b) changes the magnetic field at H_a (+ vice versa)

H_b - spinning on its axis; its spin is either \uparrow (A) or \downarrow (B)
The magnetic field it generates either adds to or subtracts from the magnetic field experienced by H_a

• Field experienced by H_a :



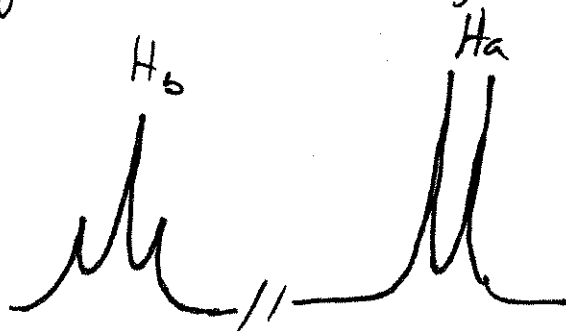
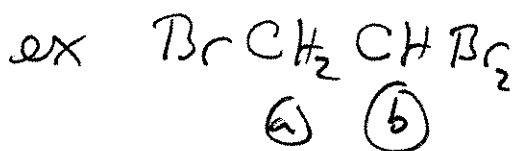
• The spacing between the lines is called the coupling constant (J)



• J arises from a magnetic field generated by another proton, therefore it is NOT dependent on the applied magnetic field
ie J is the same regardless of field strength 11-14

- Same type of splitting (for the same reason) exists for H_b . So, both are observed as doublets with the same J . (coupling constant)

N+1 Rule (in general) \rightarrow a set of N equivalent protons will split an NMR signal into $N+1$ peaks



Possible spin combinations for H_b

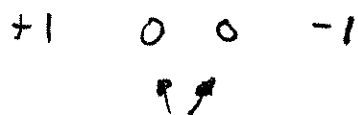
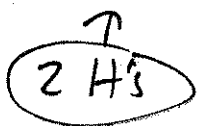


so, H_a is a doublet

Possible spin combinations for H_a

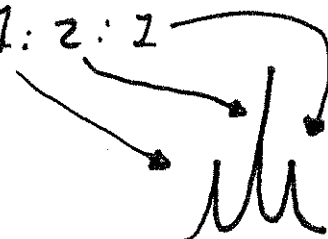


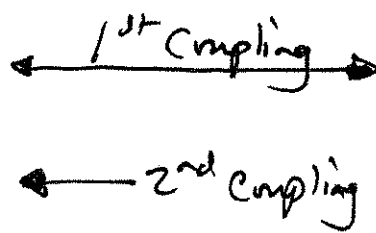
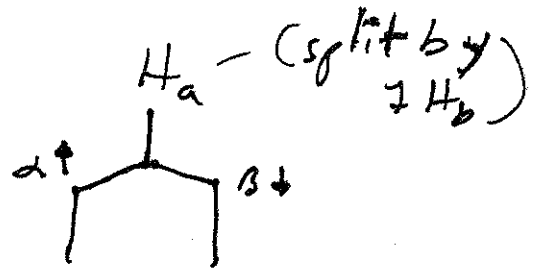
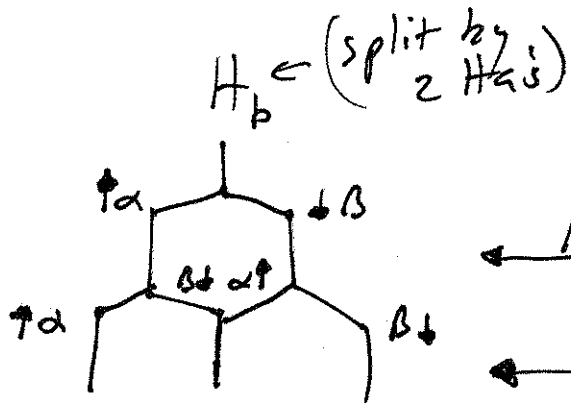
so, H_b is a triplet



The net field change is:

- Two of the combinations result in no field change at H_b , so H_b is a triplet with intensity ratios of 1:2:1

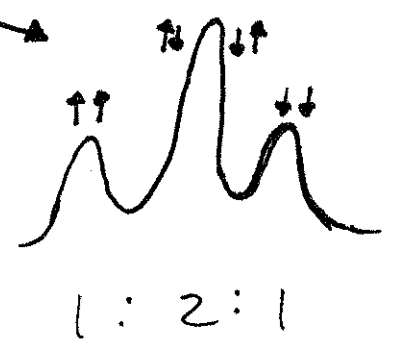




1 : 2 : 1

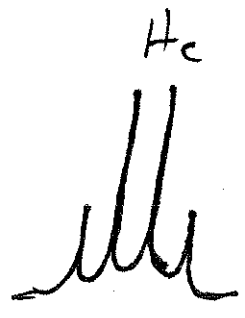
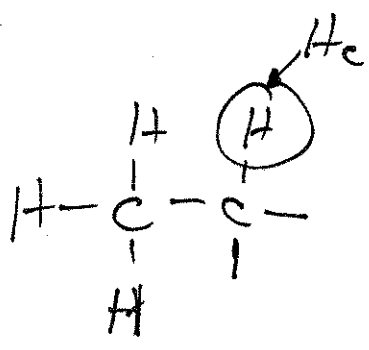
• Chemical shift reported $\frac{1}{2}$ way between the 2 lines

• Chemical shift reported center line of the triplet

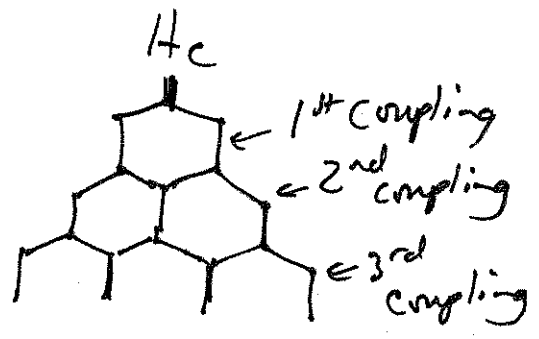


In general: δ value of a resonance reported as the center of the observed multiplet

→ By same reasoning ($\uparrow\uparrow, \downarrow\uparrow, \downarrow\downarrow$ etc) when there are 3 hydrogens on ^{an} adjacent carbon will get an $N+1 = 4$ ($3+1=4$) lines called a quartet

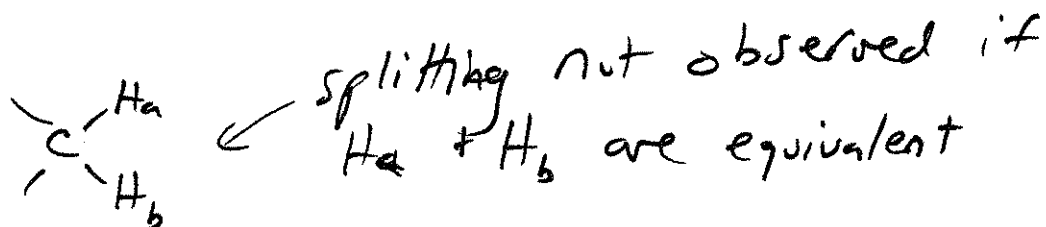


relative intensities



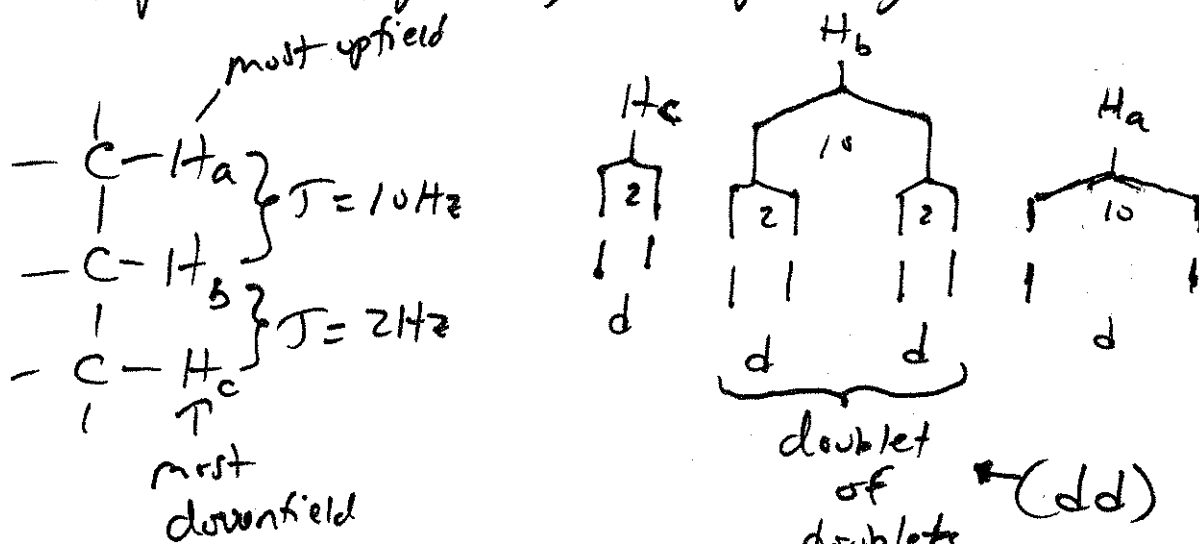
1 : 3 : 3 : 1

• Protons attached to the same carbon (geminal)



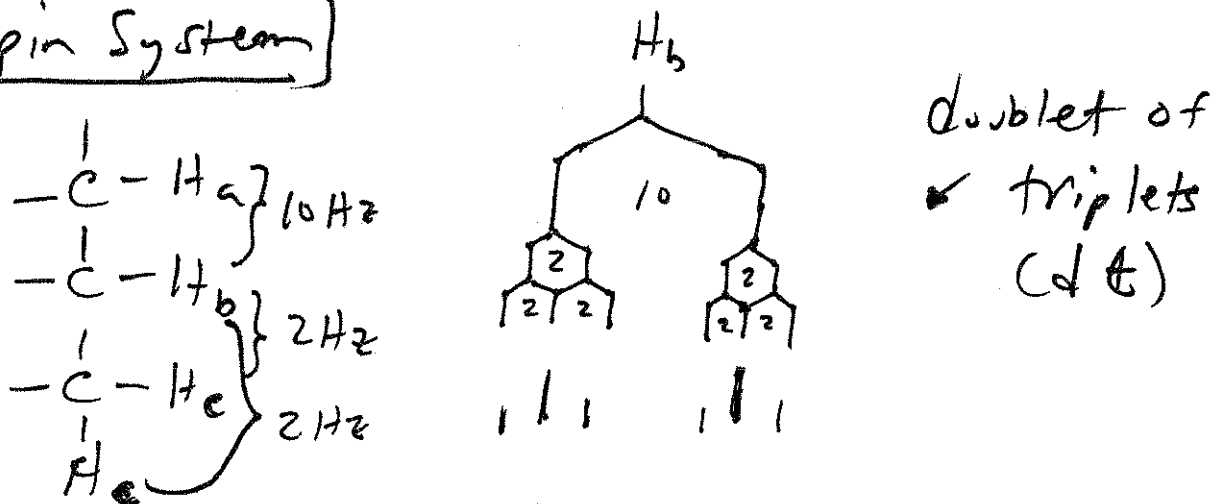
→ NMR does not distinguish between magnetically equivalent hydrogens

More complicated splitting → 3-spin system

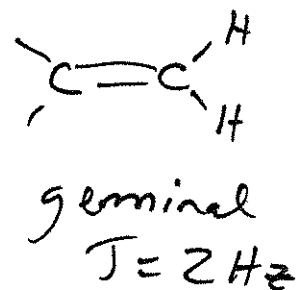
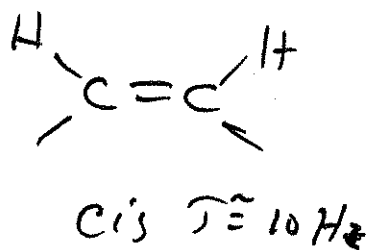
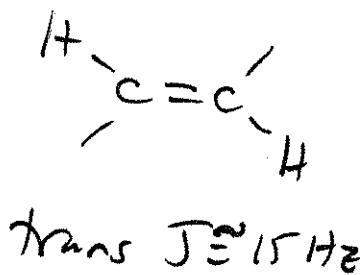


equal intensities rather than 1:3:3:1 as seen for a quartet → || ||

4-Spin System

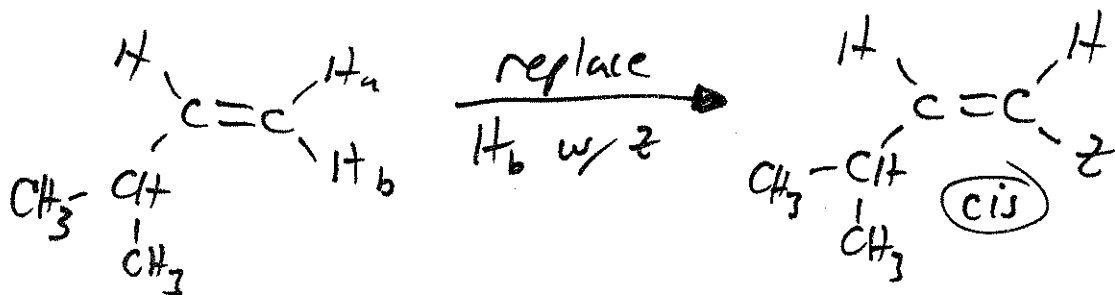
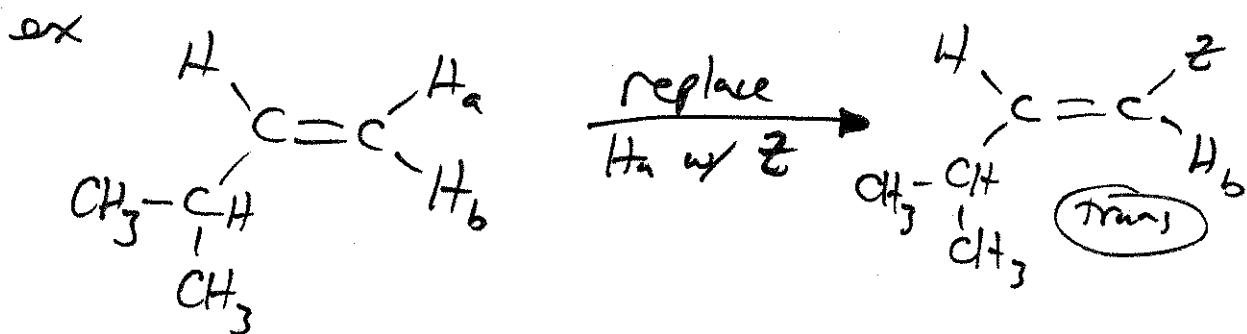


Cis and trans alkenes:



Diastereotopic protons

- protons attached to the same carbon that are magnetically nonequivalent (therefore, will couple with each other)



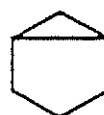
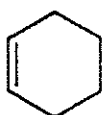
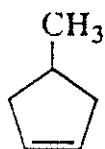
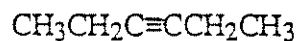
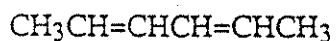
• $\text{H}_a + \text{H}_b$ are diastereotopic

INDEX OF HYDROGEN DEFICIENCY (IHD)

IHD - The number of H atoms that must be removed from C_nH_{2n+2} to give the molecular formula of the desired compound. If the triple bond is considered as two double bonds, the IHD gives the number of rings and double bonds.

Example C_6H_{10} C_nH_{2n+2} for $n = 6$ is C_6H_{14} : $IHD = (14 - 10)/2 = 2$

Some possible structures for a compound of this molecular formula are:



etc.

REMEMBER

1. Presence of O or S makes no difference in the index
2. Halogens are regarded as the equivalent of a hydrogen
3. Each N raises the number of hydrogens in the corresponding saturated parent compound by one
4. No hydrocarbon can have an odd number of hydrogens

EXAMPLES

Structure	Formula	Parent Formula	IHD	H-Deficient Structure
	C_6H_6O	C_6H_{14}	4	3 C=C, 1 ring
	$C_3H_5NO_2$	$C_3H_9NO_2$	2	1 N=O, 1 ring
$Cl_2CHCH_2C\equiv CH$	$C_4H_4Cl_2$	$C_4H_8Cl_2$	2	2 from $C\equiv C$
	C_7H_{10}	C_7H_{16}	3	1 C=C, 2 rings
	C_9H_7N	$C_9H_{21}N$	7	4 C=C, 1 C=N 2 rings

NMR Handout: Solving Unknown Structures with NMR

1. Calculate the unsaturation number (or index of hydrogen deficiency) from the molecular formula.

The overall formula, *which you should memorize*, is:

$$\text{Unsaturation Number} = \frac{2C + 2 + N - H - X}{2}$$

Where C = # of carbons, H = # of hydrogens, N = # of nitrogens, and X = # of halogens.

2. Examine the integration of the peaks. Remember that these numbers are RELATIVE areas. So, an integration of 3 peaks as 1:2:3 may actually correspond to 2:4:6 protons. The total number of protons from the integration must equal the total number in the molecular formula.

3. Examine the chemical shift of each peak. This provides information about functional groups that are near an observed proton.

4. Examine the splitting pattern to determine the number of protons adjacent to an observed proton. This will provide information about the connectivity of the molecule. Typical coupling constants will also be provided on an exam.

5. You should be able to draw an NMR spectrum from information provided in the format: δ : 1.67 (3H, t, J = 7 Hz).

6. You should also be able to determine a structure from a given molecular formula and a spectrum.

Practice Problems:

1. Give the structure of a compound $C_4H_8Cl_2$ with the following 1H NMR spectrum: δ : 1.60 (3H, d, J = 7.5 Hz), 2.15 (2H, q, J = 7.5 Hz), 3.72 (2H, t, J = 7.5 Hz), 4.27 (1H, sextet, J = 7.5 Hz).

2. C_3H_7Br : δ 1.03 (3H, t, J = 7 Hz), 1.88 (2H, sextet, J = 7 Hz), 3.40 (2H, t, J = 7 Hz).

3. $C_5H_8Br_4$: δ 3.6 (s, only 1 line in spectrum).