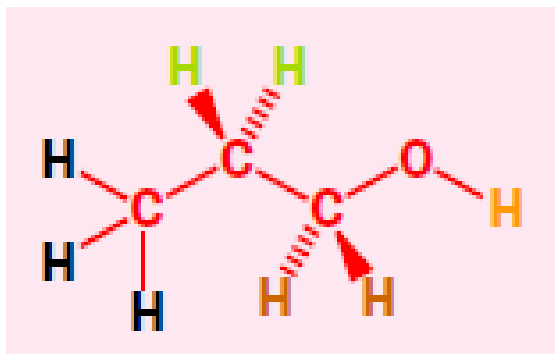# NMR Spectroscopy

Nuclear magnetic resonance (NMR)

What does it do?

Nuclear magnetic resonance (NMR) allows us to detect atomic nuclei and say what sort of environment they are in, within their molecule.

NMR can easily distinguish between different sorts of hydrogen atoms present. The technique is called ^{1}H-NMR or proton-NMR spectroscopy

Likewise, NMR can easily distinguish between the three different carbon atoms. The technique is called ^{13}C-NMR or carbon-NMR spectroscopy

One can determine the entire structure of a molecule.

Nuclear magnetic resonance (NMR)

The nuclei of all elements carry a charge.

Every nuclei have an intrinsic value of spin quantum number, I which may have value like 0, ½, 1, 2, 3, 3/2........

General guideline to have an idea about the nuclear spin quantum numbers

Mass Number	Number of Protons	Number of Neutrons	Spin (I)	Example
Even	Even	Even	0	$^{12}_{6}C(0)$, $^{16}_{8}O(0)$, $^{34}_{16}S(0)$
	Odd	Odd	Integer (1,2,...)	$^{2}_{1}H(1)$, $^{14}_{7}N(1)$, $^{10}_{5}B(3)$
Odd	Even	Odd	Half-Integer (1/2, 3/2,...)	$^{13}_{6}C(\frac{1}{2})$, $^{17}_{8}O(\frac{1}{2})$, $^{29}_{14}Si(\frac{1}{2})$
	Odd	Even	Half-Integer (1/2, 3/2,...)	$^{1}_{1}H(\frac{1}{2})$, $^{3}_{1}H(\frac{1}{2})$, $^{15}_{7}N(\frac{1}{2})$.

Nuclei having non zero spin quantum number spins around its axis

As nuclei has charge, spining nuclei generates a magnetic dipole

Each nuclei acts a tiny magnet
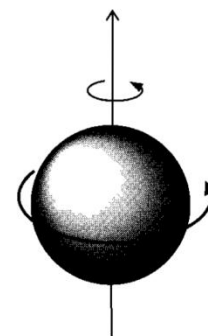
Nuclear magnetic resonance (NMR)

In the absence of an applied magnetic field, the nuclear spins are randomly oriented.

In an applied magnetic field, the nuclei twist and turn to align themselves *with or against the field of* the larger magnet.

More energy is needed for a proton to align against the field than with it.

Protons that align with the field are in the lower-energy α-spin-state; protons that align against the field are in the higher-energy β-spin-state
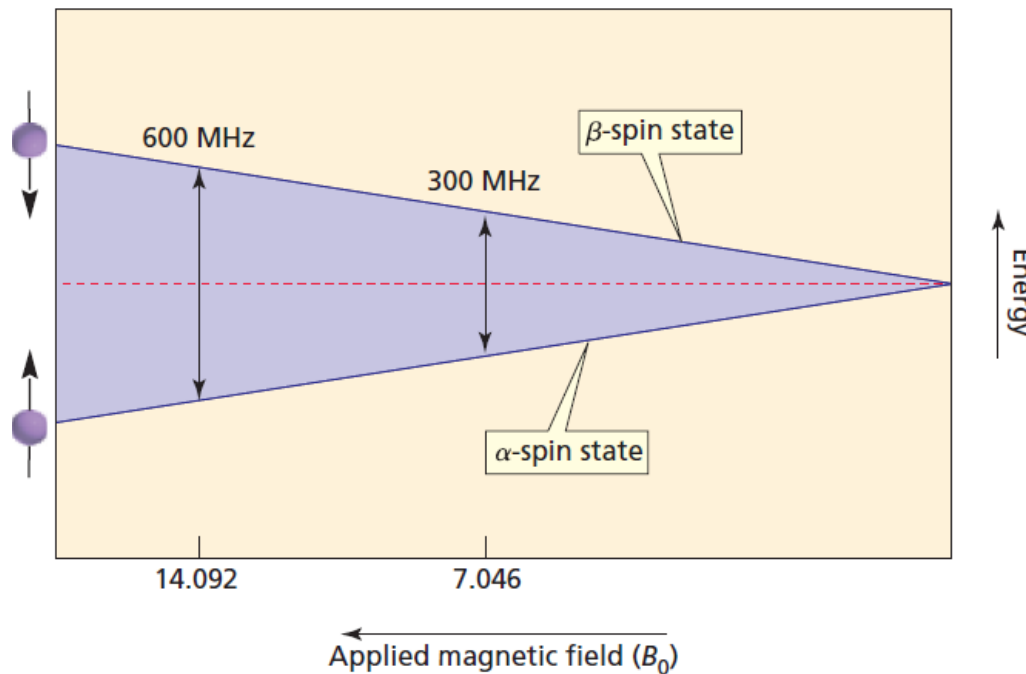
More nuclei are in the α-state than in the β-state.
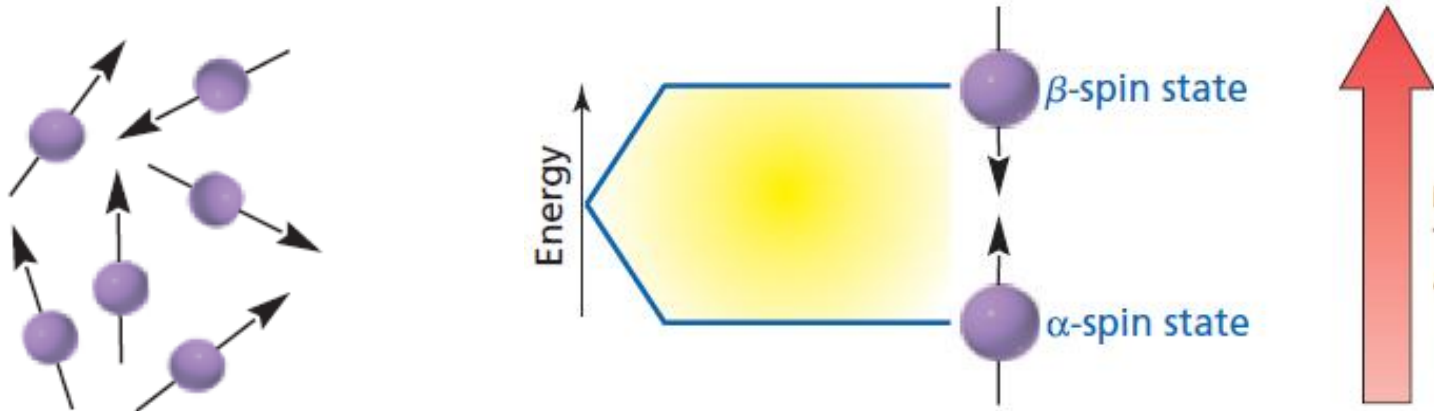
Nuclear magnetic resonance (NMR)

The energy difference between the α-and β-states depends on the strength of the **applied magnetic field**

The greater the strength of the magnetic field to which nucleus is exposed, the greater is the difference in energy between the α-and β-states

The earth's magnetic : 2×10^{-5} tesla.
A typical NMR-magnet:
between 2 and 10 tesla
10^5 times stronger than the earth's field.

Now here is an unfortunate thing about NMR
The energy difference between the nuclear spin being aligned with the magnetic field and against it is really *very small*
so small that we need a very, very strong magnetic field to see any difference at all.

Nuclear magnetic resonance (NMR)

When a nuclei is subjected to a corresponding to the difference in energy between the α-and β-states, nuclei in the α-state are promoted to the β-state.
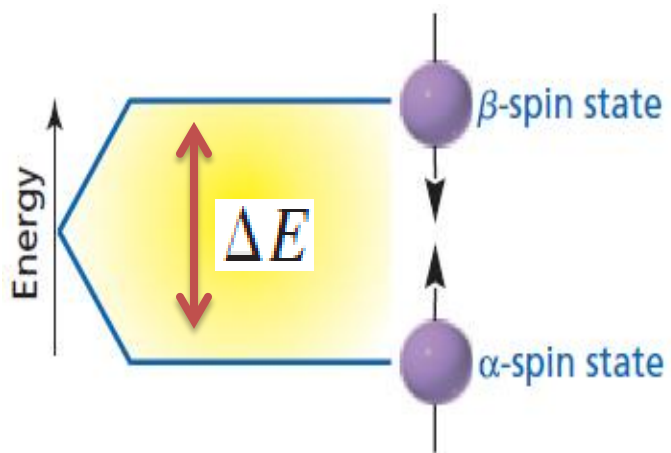
Because the energy difference between the and states is so small only a small amount of energy is needed to flip the spin.

The radiation required is in the radiofrequency (rf) region of the electromagnetic spectrum and is called **rf radiation.**

When the nuclei undergo relaxation (i.e., return to their original state), they emit electromagnetic signals whose frequency depends on the difference in energy between the α- and β-states.

The NMR spectrometer detects these signals and displays them as a plot of signal frequency versus intensity—an NMR spectrum.

Nuclear magnetic resonance (NMR)

Energy difference (**ΔE**) between the spin states depends on the operating frequency (**v**) of the spectrometer, which in turn depends on the strength of the magnetic field (**B_0**), and the *gyromagnetic ratio (γ)*

$$\Delta E = h\nu = h\frac{\gamma}{2\pi}B_0$$

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

The **gyromagnetic ratio (also called the magnetogyric ratio) is a constant that** depends on the magnetic moment of the particular kind of nucleus.

$$\gamma\ (^1H) = 2.675 \times 10^8\ T^{-1}\ s^{-1}$$
$$\gamma\ (^{13}C) = 6.688 \times 10^7\ T^{-1}\ s^{-1}$$

Operating frequency of a particular spectrometer is the radio frequency required to flip the spin of a particular nucleus in that **spectrometer**

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

$$= \frac{2.675 \times 10^8}{2(3.1416)}T^{-1}s^{-1} \times 7.046\,T$$

$$= 300 \times 10^6\,Hz = 300\,MHz$$

A NMR spectrometer is equipped with a magnet with a magnetic field (**B_0 = 7.046 T)** the spectrometer will require an operating frequency of 300 MHz for proton to flip the spin

Nuclear magnetic resonance (NMR)

What frequency (in MHz) is required to cause a ^{13}C to flip its spin when it is exposed to a magnetic field of B_0 = 7.046 T ?

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

$\gamma\ (^{13}C) = 6.688 \times 10^7\ T^{-1}\ s^{-1}$

$$= \frac{6.688 \times 10^7}{2(3.1416)} T^{-1}s^{-1} \times 7.046\ T$$

$$= 75 \times 10^6\ Hz$$

An NMR spectrometer with a magnet requiring a frequency of **300 MHz** to flip the spin of an **^1H** nucleus requires a frequency of **75 MHz** to flip the spin of a **^{13}C** nucleus.

What frequency (in MHz) is required to cause an unsheilded proton to flip its spin when it is exposed to a magnetic field of 1 tesla?

Nuclear magnetic resonance (NMR)

1 The sample of the compound is dissolved in a suitable solvent and put in a very strong magnetic field.

2 The sample is irradiated with a short pulse of radiofrequency. This disturbs the equilibrium balance between the two energy levels: some nuclei absorb the energy and are promoted to a higher energy level

3 We then detect the energy given out when the nuclei fall back down to the lower energy level using a sophisticated radio receiver

4 After lots of computation, the results are displayed in the form of intensity (i.e. number of absorptions) against frequency.
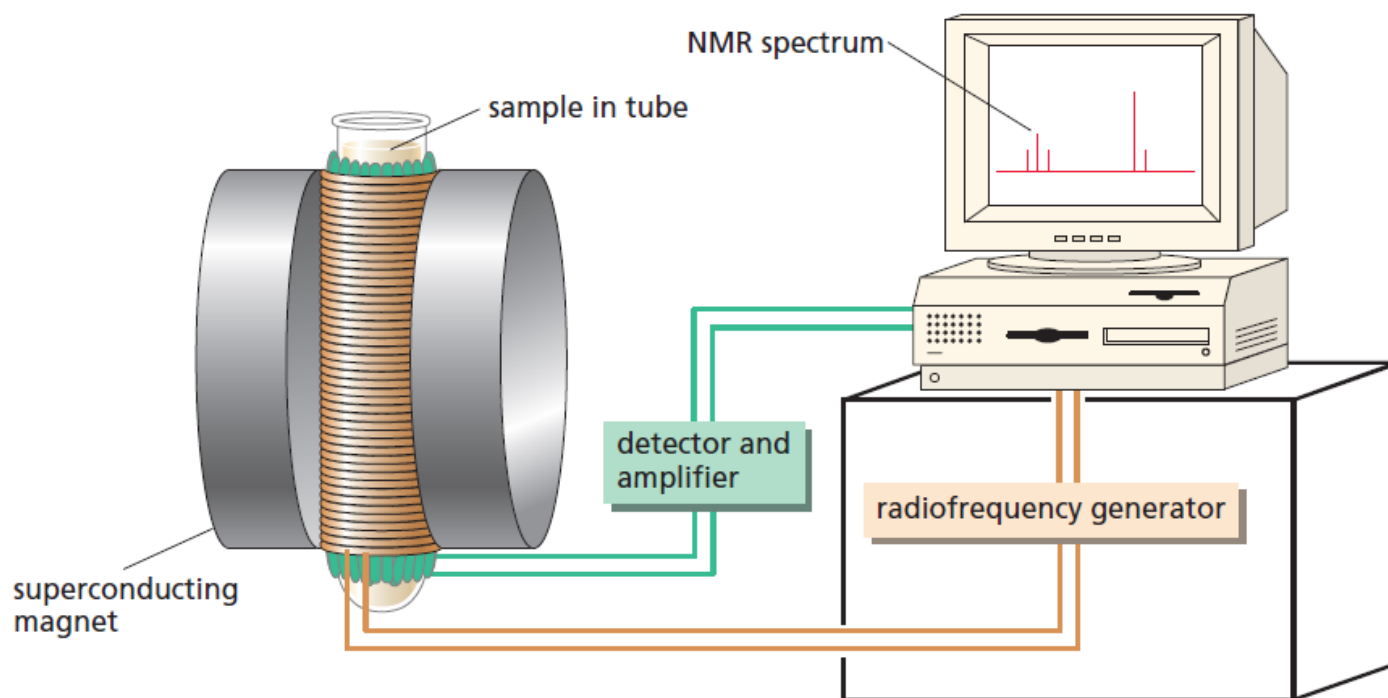
Nuclear magnetic resonance (NMR)

Why do chemically distinct nuclei absorb energy at different frequencies?

two factors that affect the energy difference (and therefore the frequency): the magnetic field strength and what sort of nucleus is being studied.

So you might expect all carbon-13 nuclei to resonate at one particular frequency and all protons(1H) to resonate at one (different) frequency.

But they don't.

shielding of nuclei from an applied magnetic field by electrons:

applied magnetic field

small induced magnetic field shielding the nucleus

$$B_{\text{effective}} = B_{\text{applied}} - B_{\text{local}}$$
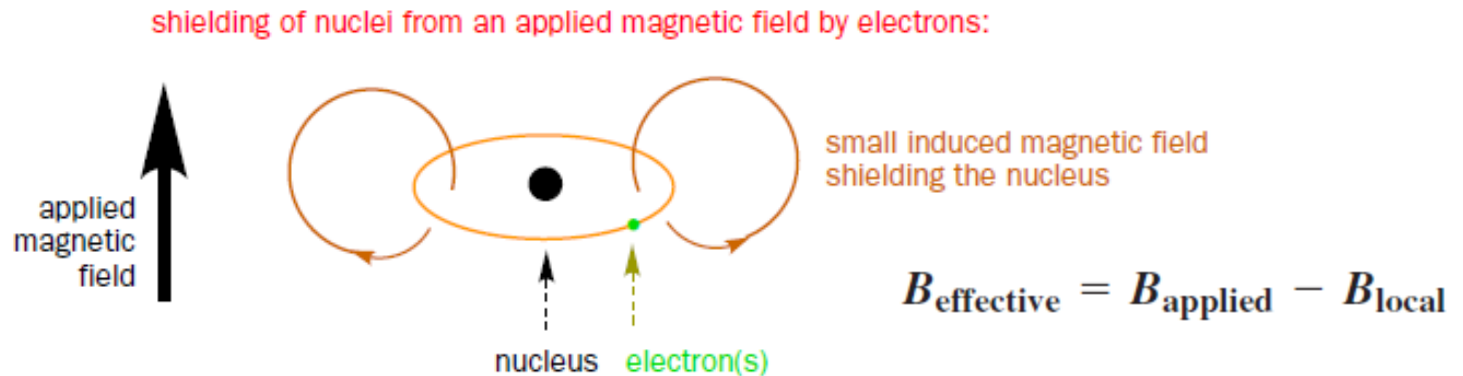
nucleus   electron(s)

Each nucleus is surrounded by electrons, and in a magnetic field these will set up a tiny electric current. This current will set up its own magnetic field, which will oppose the magnetic field that we apply.

The electrons are said to **shield the nucleus from the external magnetic field.**
If the electron distribution varies from 13C atom to 13C atom
so does the local magnetic field
and so does the effective magnetic field and resonating frequency of the 13C nuclei.

Nuclear magnetic resonance (NMR)

The carbon attached to the OH group will have relatively fewer electrons around it compared to the other carbon since the oxygen atom is more electronegative and draws electrons towards it, away from the carbon atom.
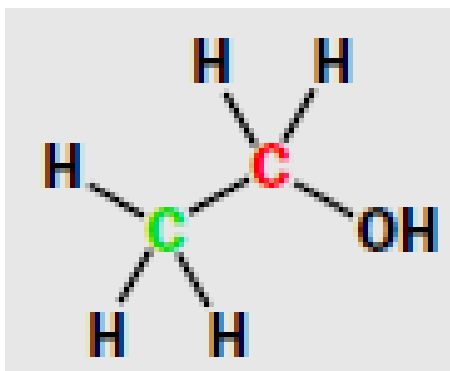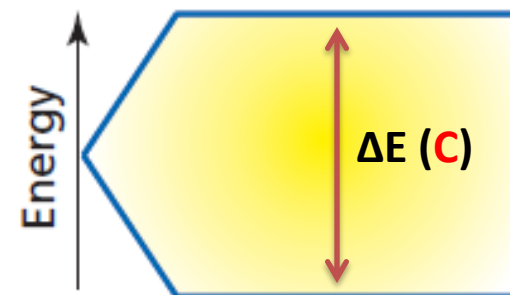
$$B_{\text{effective}} = B_{\text{applied}} - B_{\text{local}}$$

B_{loc} (C) < B_{loc} (C)

B_{eff} (C) > B_{eff} (C)

ΔE (C) > ΔE (C)

(C) is called more shielded compared to (C)
Or
(C) is more deshielded compared to (C)

Larger is deshielding higher will be the resonance frequency

ΔE (C)

ΔE (C)

(C)

(C)

(solvent)

200   150   100   50   0
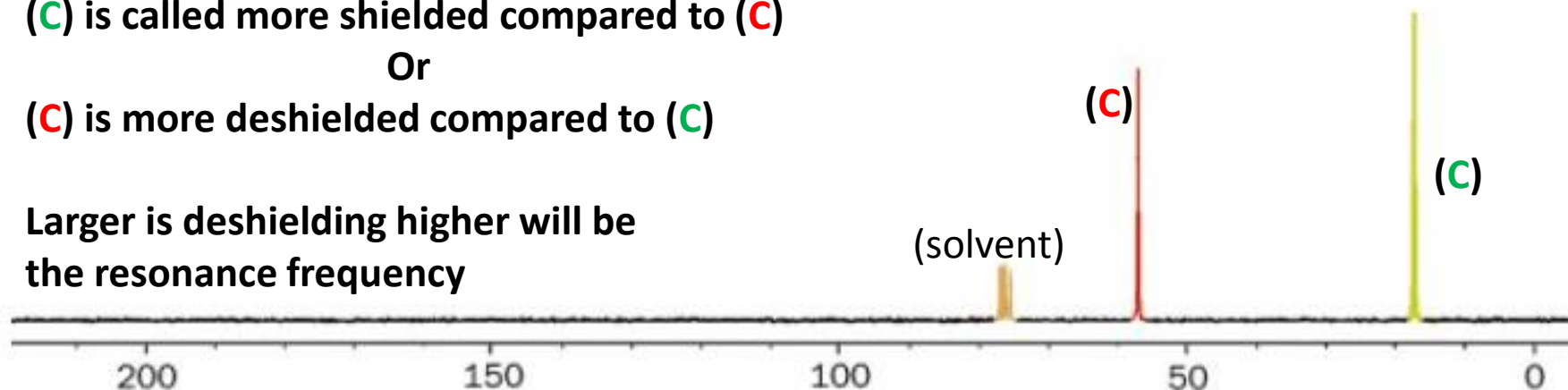
13C- NMR spectrum of ethanol in CDCl$_3$

Nuclear magnetic resonance: Chemical Shift

The exact frequency at which the nucleus resonates depends on the external applied magnetic field.

This means that, if the sample is run on a machine with a different magnetic field, it will resonate at a different frequency.

The resonance frequency is measured with respect to that of a reference sample (to represent the resonance frequency with a value independent of operating frequency i.e. strength of the magnet)

The relative resonance frequency is termed as **chemical shift**, which is a measure of how far the signal is from the reference TMS signal.

$$CH_3—Si—CH_3$$
with CH_3 above and CH_3 below the Si

tetramethylsilane
TMS
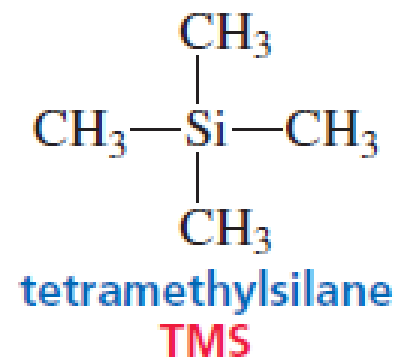
The chemical shift, δ, in parts per million (p.p.m.)

$$\delta = \frac{\text{Resonance frequency (Hz)} - \text{frequency of TMS (Hz)}}{\text{operating frequency of the spectrometer (MHz)}}$$

By definition TMS itself resonates at 0 p.p.m.

Nuclear magnetic resonance: Chemical Shift

66.0 (saturated carbon next to oxygen)

lactic acid (2-hydroxypropanoicacid)
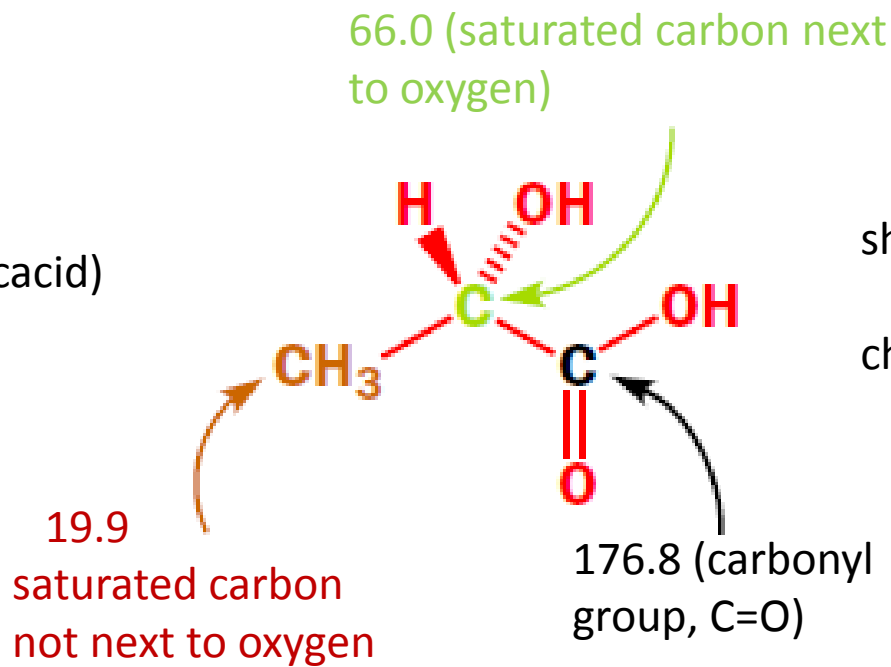
shielding order : (C) < (C) < (C)

chemical shift (δ): (C) > (C) > (C)

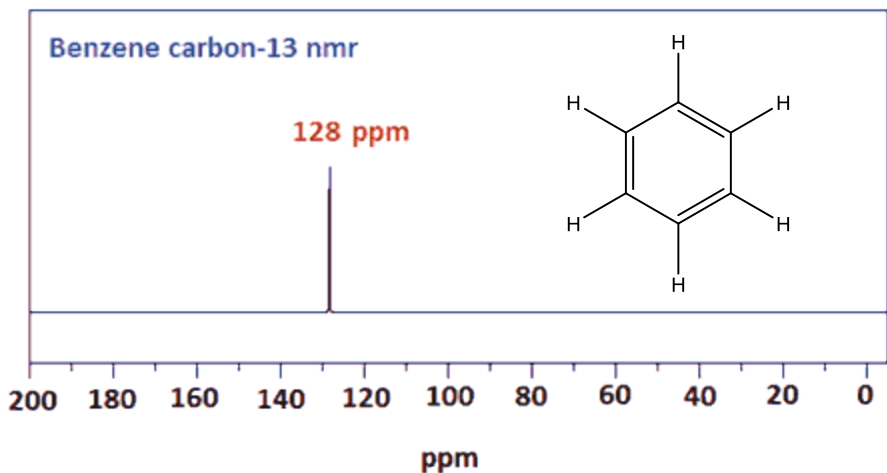19.9 saturated carbon not next to oxygen

176.8 (carbonyl group, C=O)
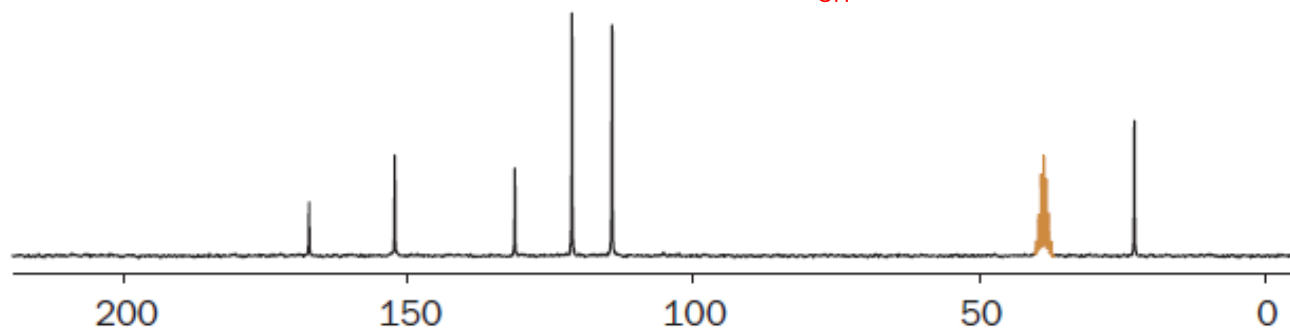
(solvent)
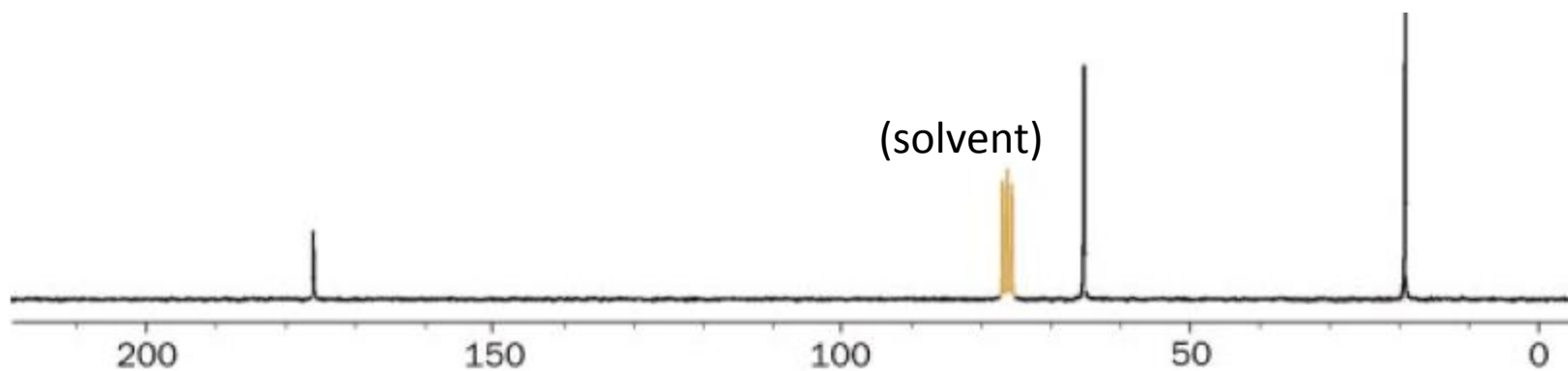
13C- NMR spectrum of lactic acid in $CDCl_3$

The Number of Signals

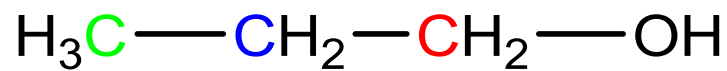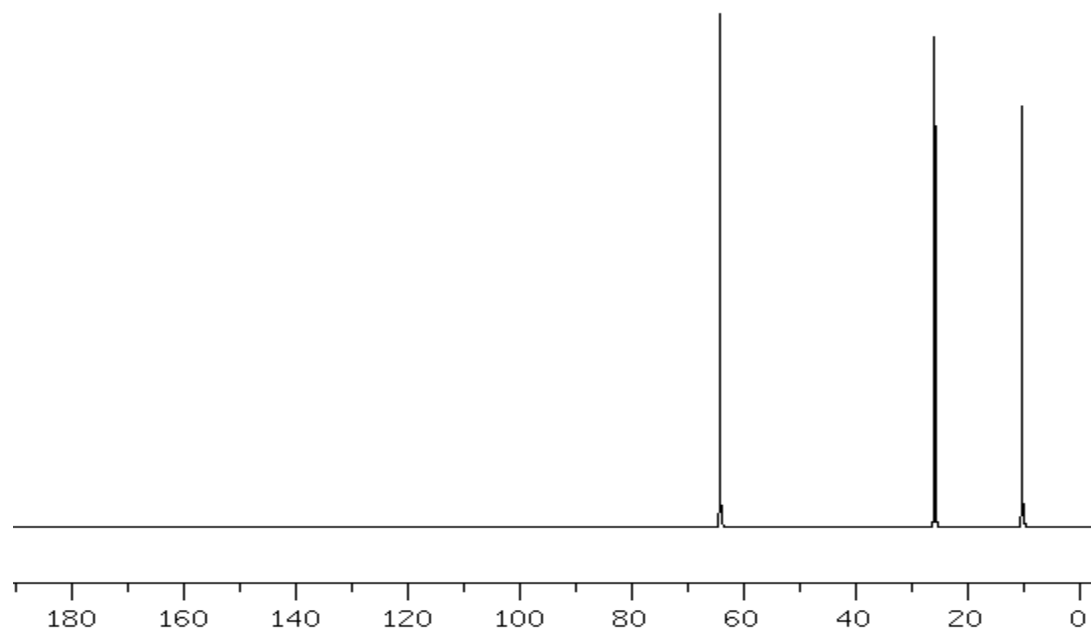Carbon in the same environment are called **chemically equivalent carbon.**

Each set of chemically equivalent carbon in a compound gives rise to a signal in the ^{13}C-NMR spectrum of that compound.
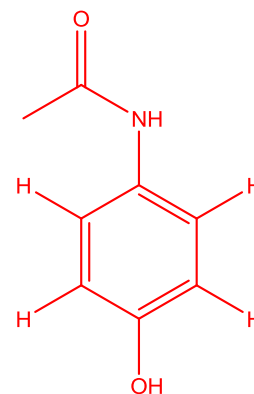
paracetamol

Sometimes the signals are not sufficiently separated and overlap each other

H_3C—CH_2—CH_2—OH

1-propanol (C_3H_8O)

CH_3
|
H_3C—CH—OH
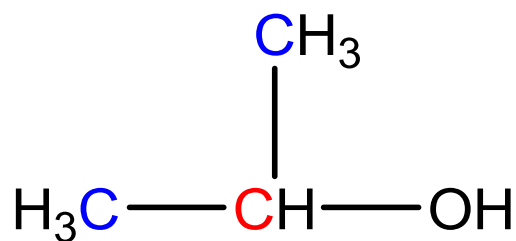
2-propanol (C_3H_8O)
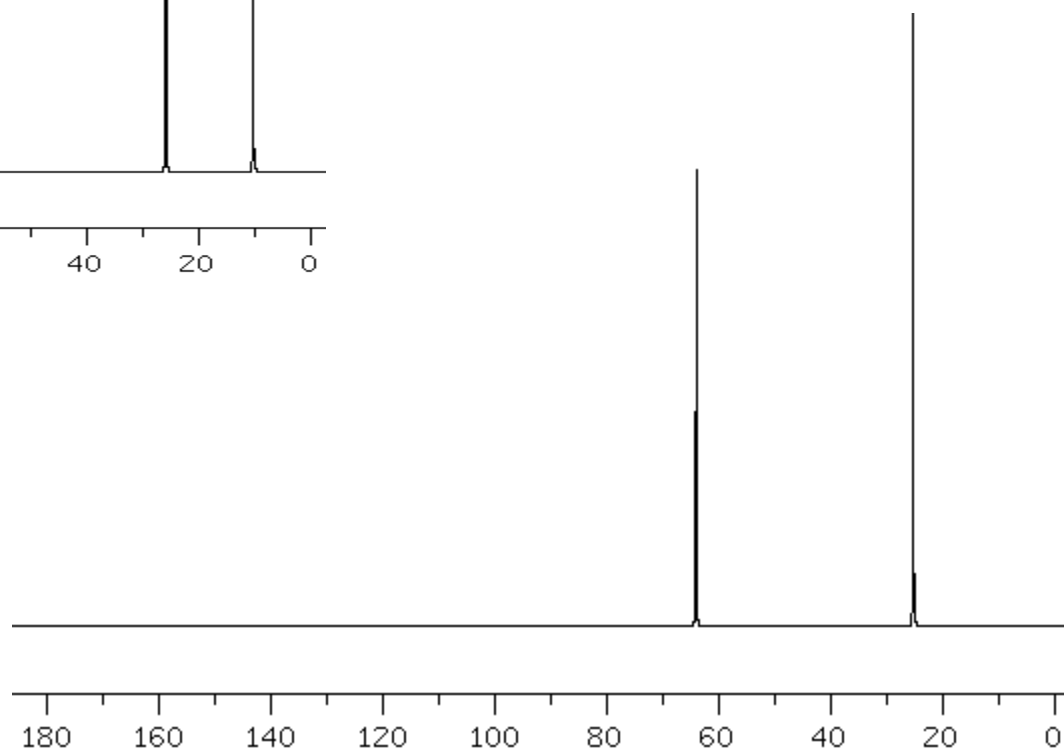
From ^{13}C-NMR you can say the alcohol given to you is 2-propanol or 1-propanol

¹H-NMR Spectroscopy

¹H-NMR Spectroscopy

Except carbon, other major component of the organic molecule is hydrogen atom

Important structural information will be obtain, if we can distinguish between different sorts of hydrogen atoms present

¹H nuclei behave similarly as a ¹³C nuclei does in the magentic field because they have same sipn number I = ½
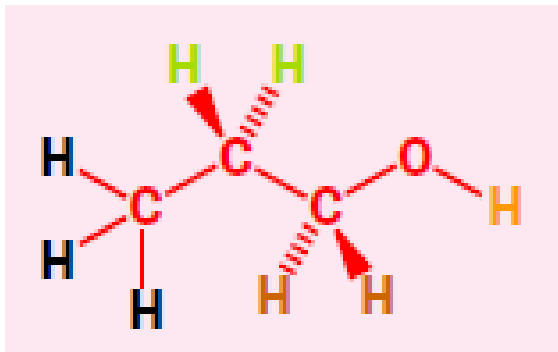
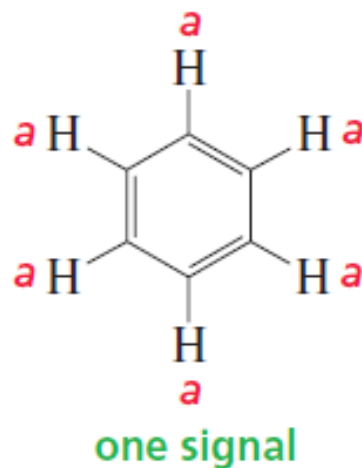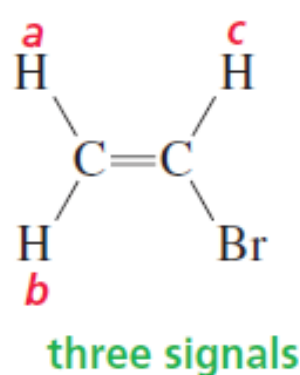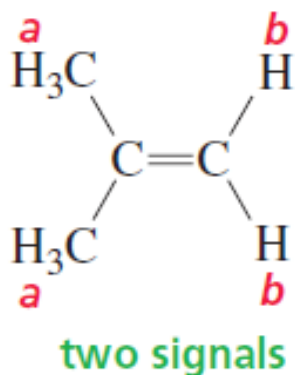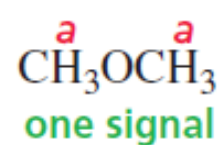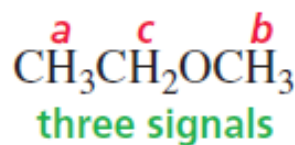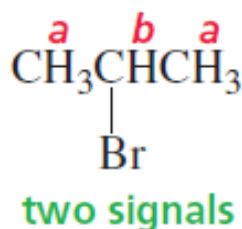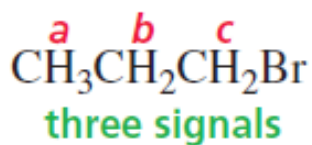The number of signals in a ¹H-NMR spectrum tells you how many different kinds of Hydrogen a compound has—just as the number of signals in an ¹³C-NMR spectrum tells you how many different kinds of carbon a compound has.

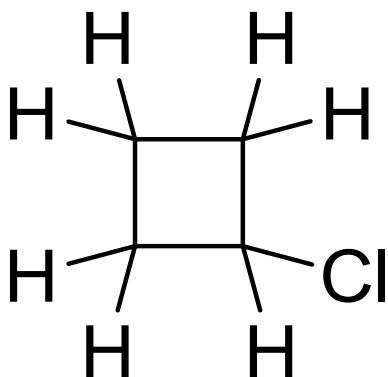The principles behind ¹H-NMR and ¹³C-NMR spectroscopy are essentially the same.

The Number of Signals in the ^{1}H-NMR Spectrum

Like carbon, **a set of equivalent protons** gives rise to a signal

a   *b*   *c*
$CH_3CH_2CH_2Br$
three signals

a   *b*   *a*
CH_3CHCH_3
|
Br
two signals

a   *c*   *b*
$CH_3CH_2OCH_3$
three signals

a   *a*
CH_3OCH_3
one signal

$$CH_3$$
$$|$$
$$CH_3COCH_3$$
$$|$$
$$CH_3$$

a   *b*
H_3C H
         $C=C$
H_3C H
a   *b*
two signals

a   *c*
H   H
         $C=C$
H   Br
b
three signals

a
H
a H   H *a*

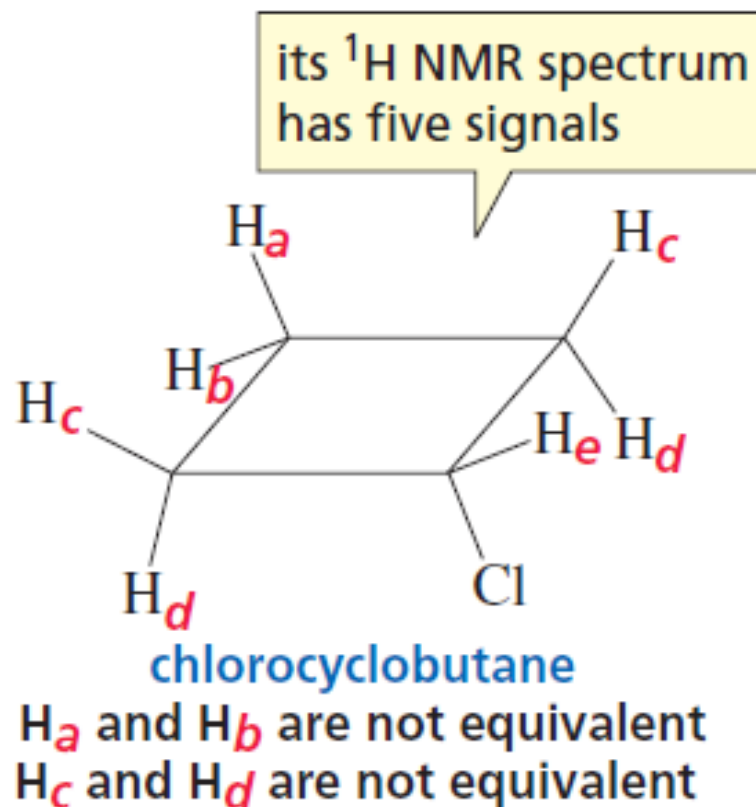*a* H   H *a*
H
a
one signal

NO_2
H   H

H   H
H
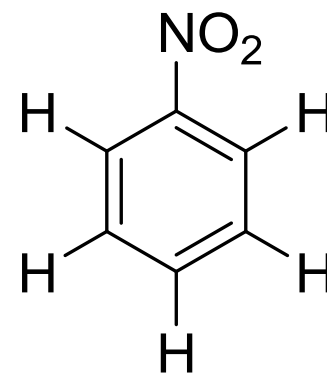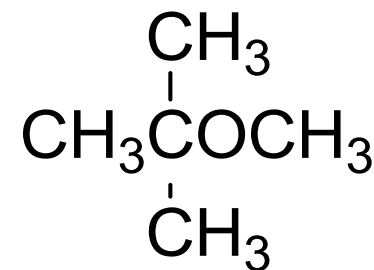
One can tell how many sets of equivalent protons a compound has from the number of signals in its ^{1}H-NMR spectrum

The Number of Signals in the ^{1}H-NMR Spectrum

its ^{1}H NMR spectrum has five signals

chlorocyclobutane
H$_a$ and H$_b$ are not equivalent
H$_c$ and H$_d$ are not equivalent

Sometimes, two protons on the same carbon are not equivalent

Even though they are bonded to the same carbon, the **H$_a$** and **H$_b$** protons are not equivalent because they are not in the same environment: **H$_a$** is trans to Cl and **H$_b$** is cis to Cl.
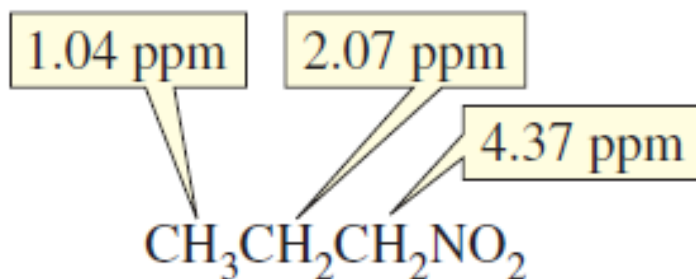
Chemical Shifts

Chemical shifts are measured using TMS as reference compound
Most proton chemical shifts fall in the range from 0 to 10 ppm
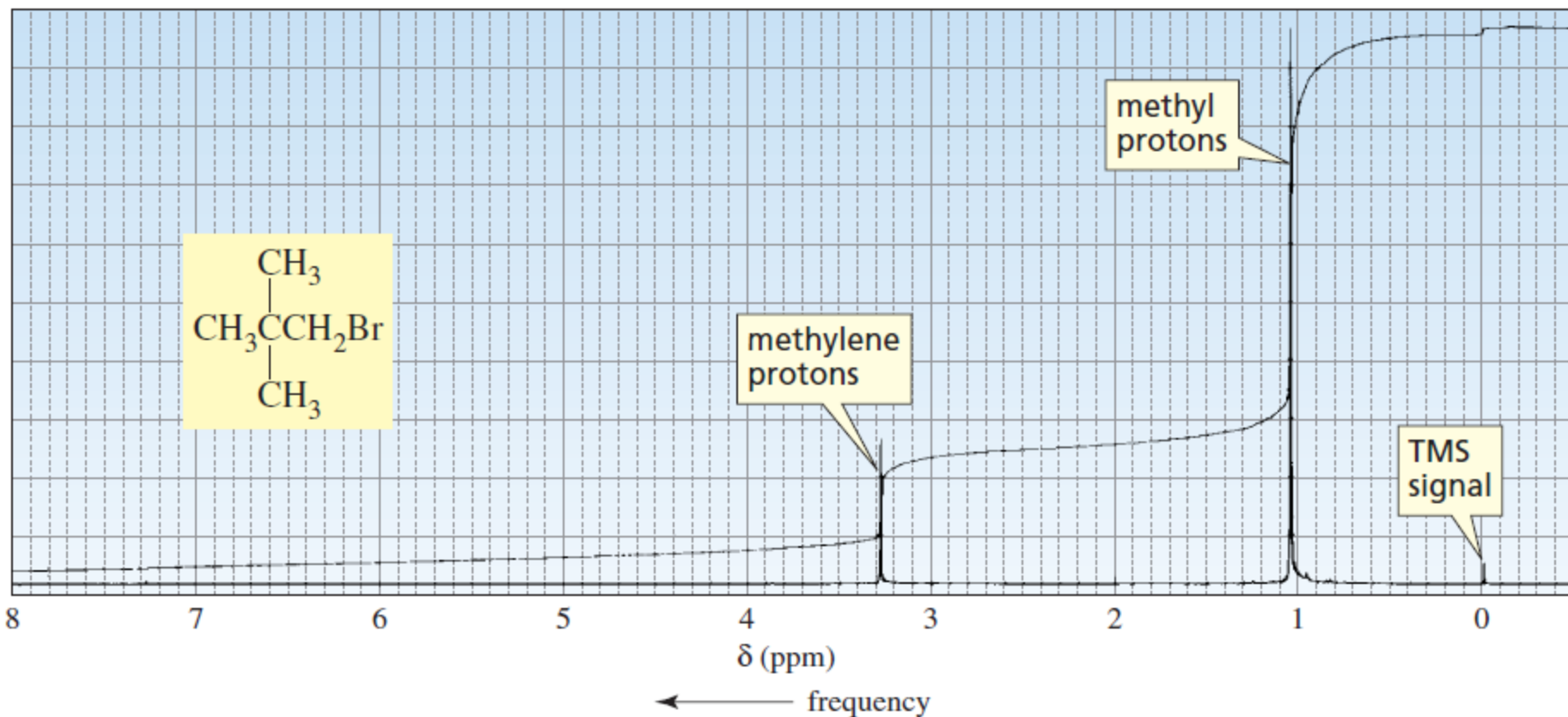
The Relative Positions of ^{1}H-NMR Signals

1.04 ppm   2.07 ppm

4.37 ppm

$CH_3CH_2CH_2NO_2$

protons in electron-poor environments	protons in electron-dense environments
deshielded protons	shielded protons
downfield	upfield
high frequency	low frequency
large δ values	small δ values

$CH_3CH_2CH_2CH_2CH_2F$ $CH_3CH_2CH_2CH_2CH_2Cl$

$CH_3CH_2CH_2CH_2CH_2Br$ $CH_3CH_2CH_2CH_2CH_2I$
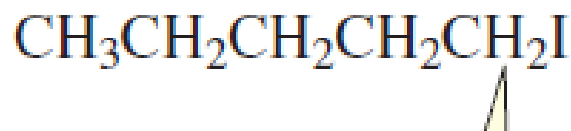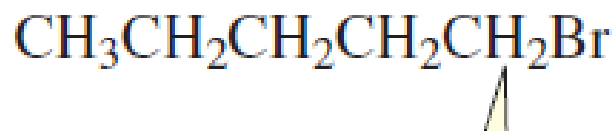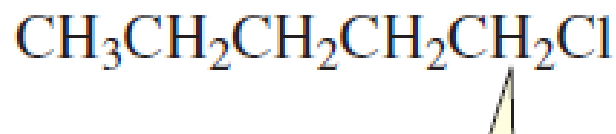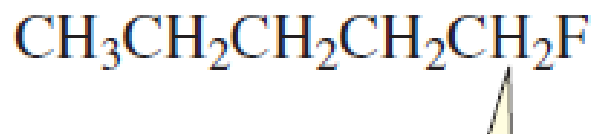
Integration of NMR Signals: Number of Proton

The area under each signal is proportional to the number of protons that gives rise to the signal

Area under a curve can be determined by integration

The integrals can also be displayed by a line of integration superimposed on the original spectrum

The height of each integration step is proportional to the area under that signal, which, in turn, is proportional to the number of protons giving rise to the signal
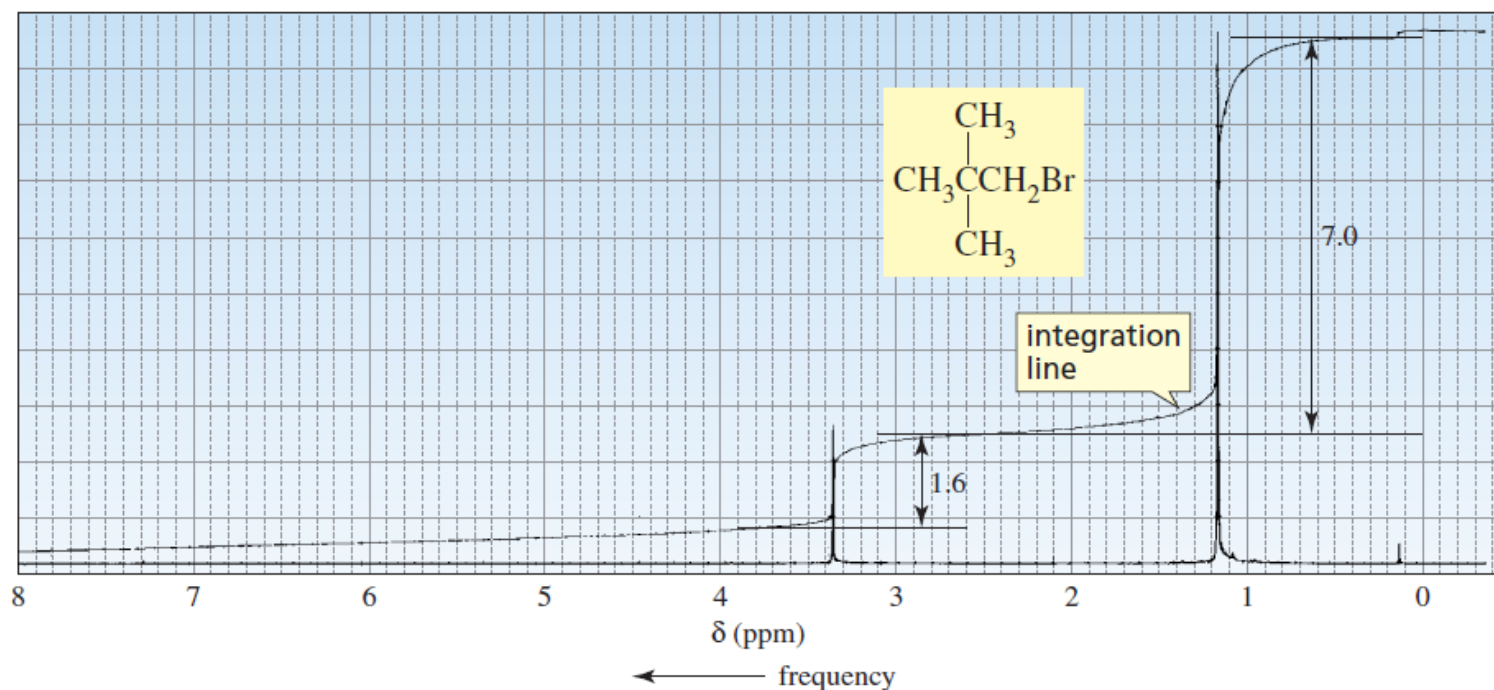
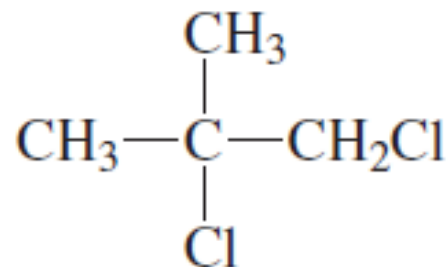The **integration tells us the** *relative number of protons that give rise to each signal,* not the *absolute number*

Integration of NMR Signals: Number of Proton

10 : 15 or 2: 3

10

15

^1H NMR

solvent

10

5

0 p.p.m.

$CH_3—CH—Cl$

Cl
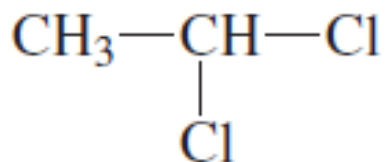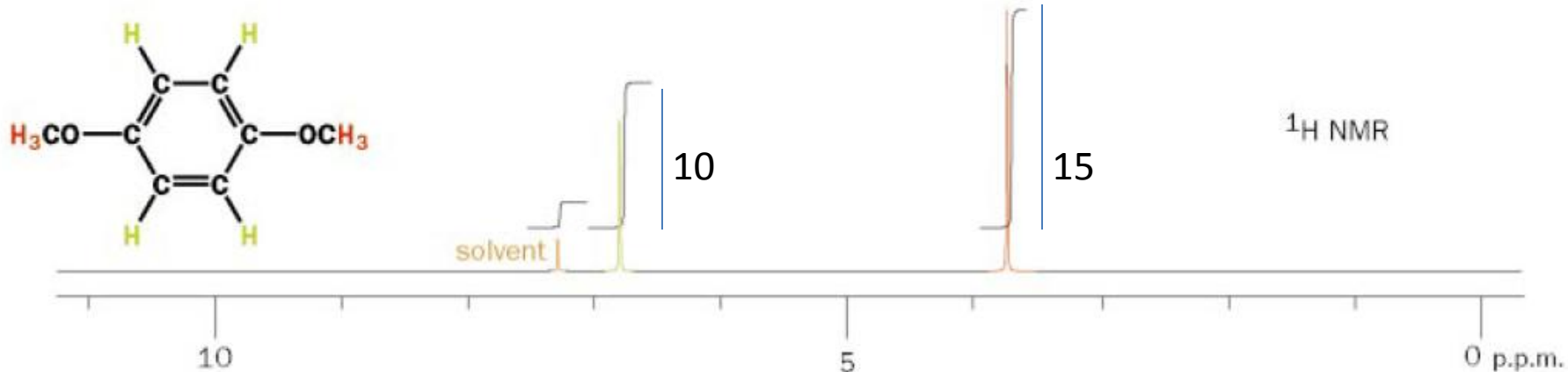
1,1-dichloroethane
ratio of protons = 1:3

$CH_3—C—CH_2Cl$

CH₃ above, Cl below

1,2-dichloro-2-methylpropane
ratio of protons 2:6 = 1:3

Coupling in the proton NMR spectrum

Nearby hydrogen nuclei interact and give multiple peaks via spliting the peaks. The interaction between nearby protons known as **coupling.**

Splitting is caused by protons bonded to adjacent (i.e., directly attached) carbons. The splitting of a signal is described by **N + 1** the where *N is the number of equivalent* protons bonded to *adjacent carbons.*

By "equivalent protons," we mean that the protons bonded to an adjacent carbon are equivalent to each other, but not equivalent to the proton giving rise to the signal.
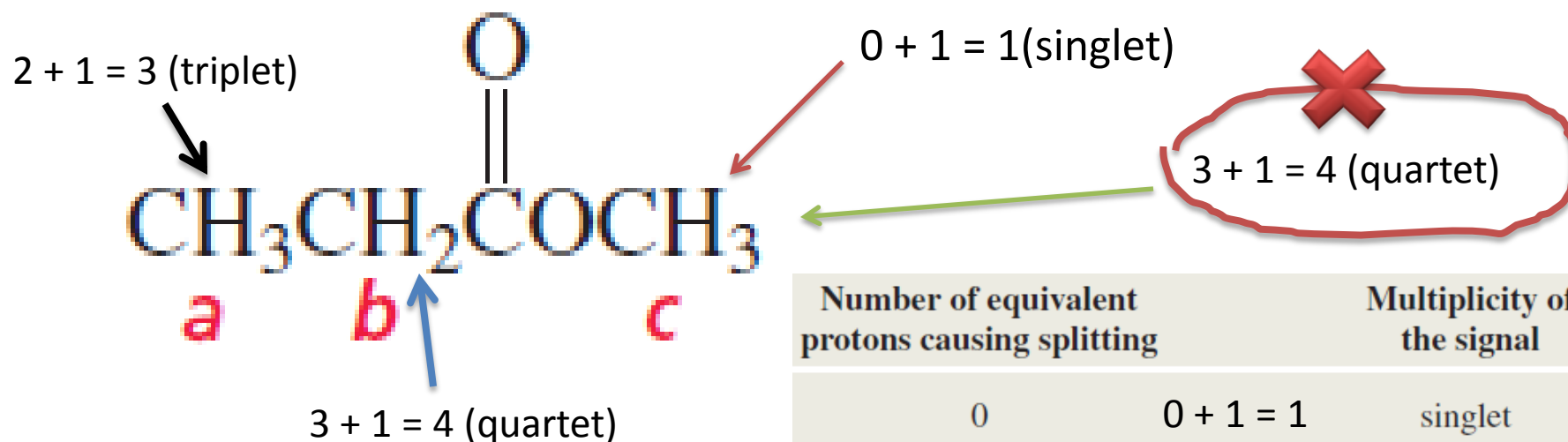

(3+ 1) = 4 peaks

CH_3CHCl_2

(1+ 1) = 2 peaks

δ (ppm)
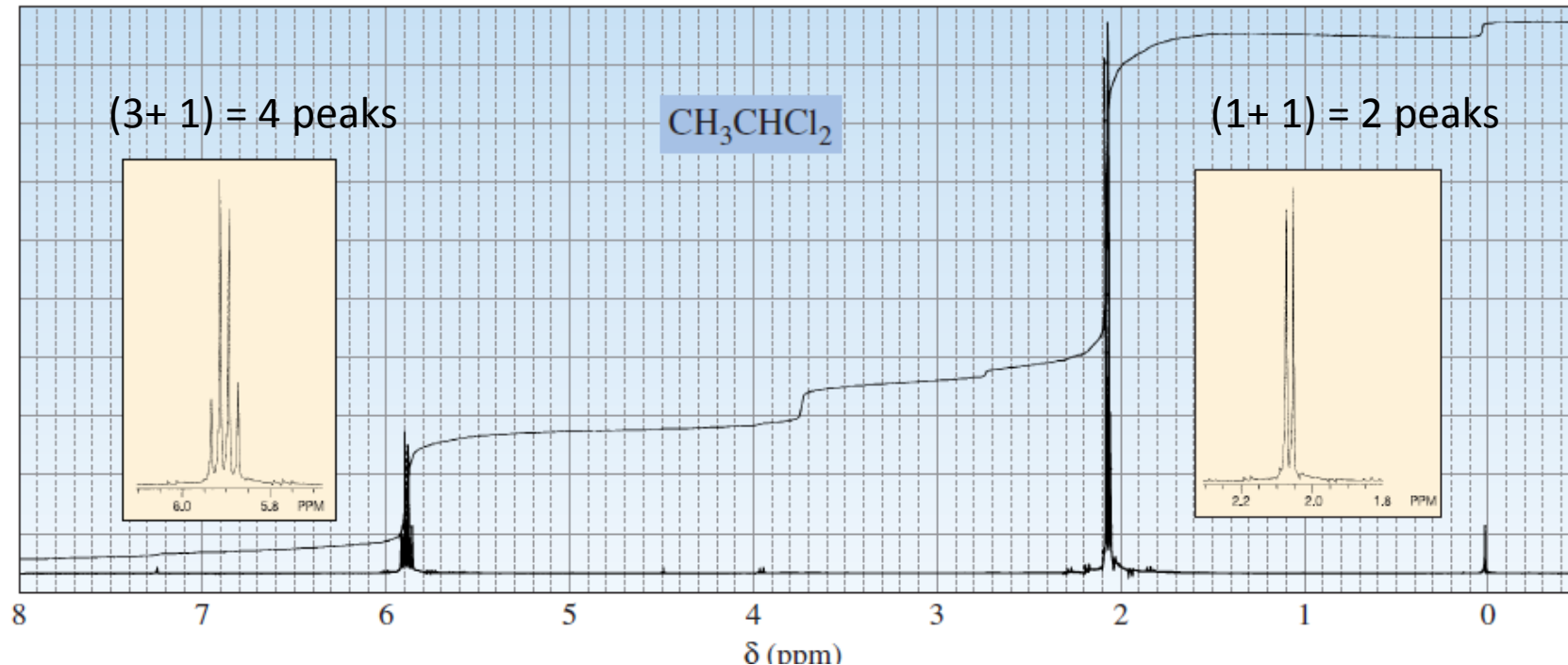
Coupling in the proton NMR spectrum

*it is **not** the number of **protons giving rise to a signal** that determines the multiplicity of the signal*

*it **is** the number of protons **bonded to the immediately adjacent carbons** that determines the multiplicity.*

2 + 1 = 3 (triplet)

0 + 1 = 1(singlet)

3 + 1 = 4 (quartet)

$$CH_3CH_2COCH_3$$

a   b   c

3 + 1 = 4 (quartet)

> 7 are considered as multiplet

| Number of equivalent protons causing splitting		Multiplicity of the signal
0	0 + 1 = 1	singlet
1	1 + 1 = 2	doublet
2	2 + 1 = 3	triplet
3	3 + 1 = 4	quartet
4	4 + 1 = 5	quintet
5	5 + 1 = 6	sextet
6	6 + 1 = 7	septet

Coupling in the proton NMR spectrum

H_a and H_b split each other's signal because they are separated by three σ bonds
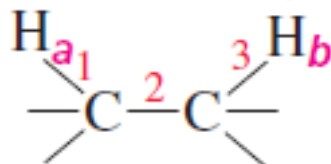
H_a and H_b do not split each other's signal because they are separated by four σ bonds
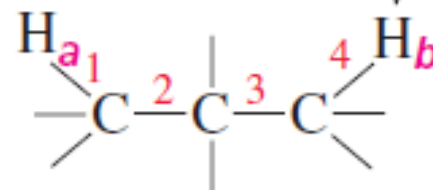
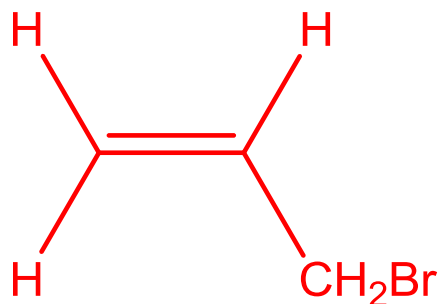How many signal can be found in 1H-NMR spectrum of the following compound? What would be the splitting pattern of the signal?

$$Cl—CH_2—CH_2—Cl$$
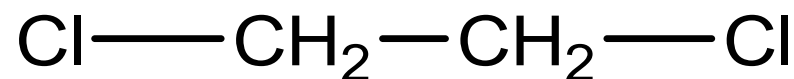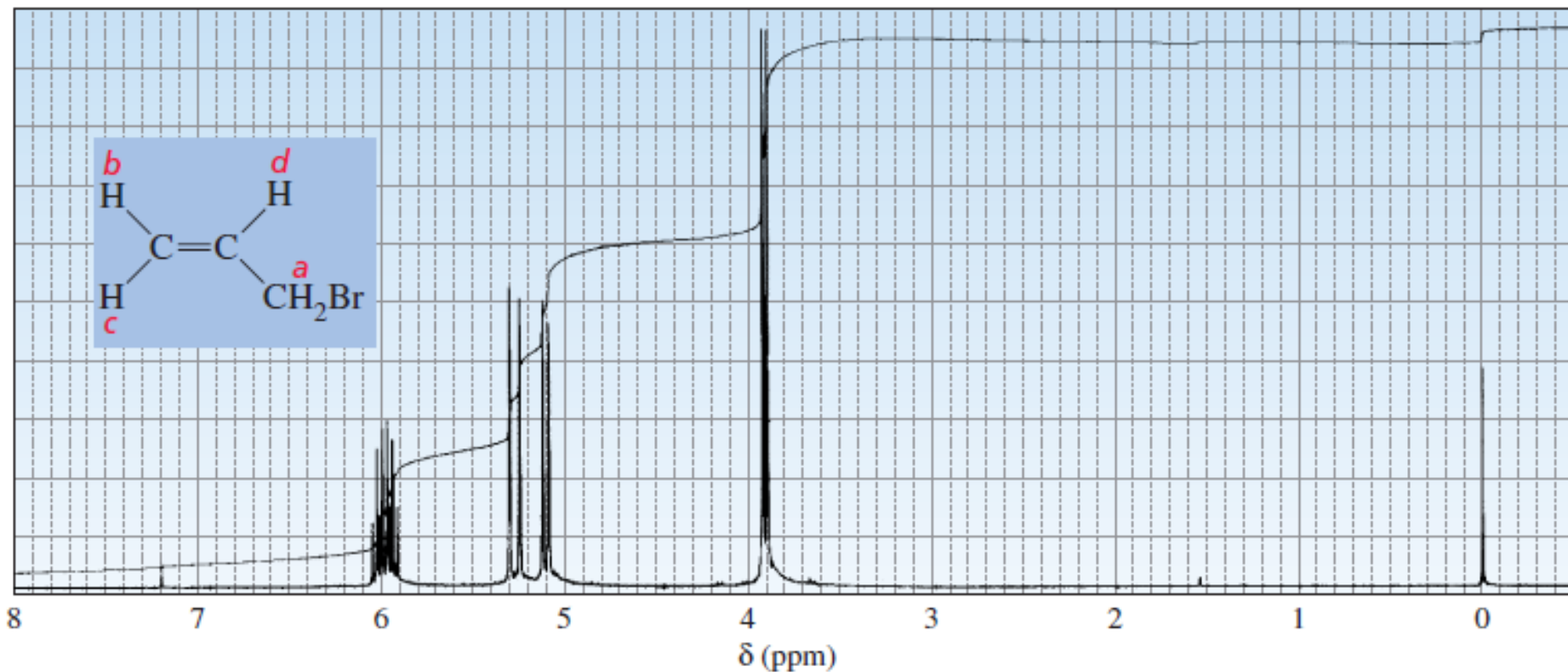
1,2-dichloroethane has an NMR spectrum that shows one singlet

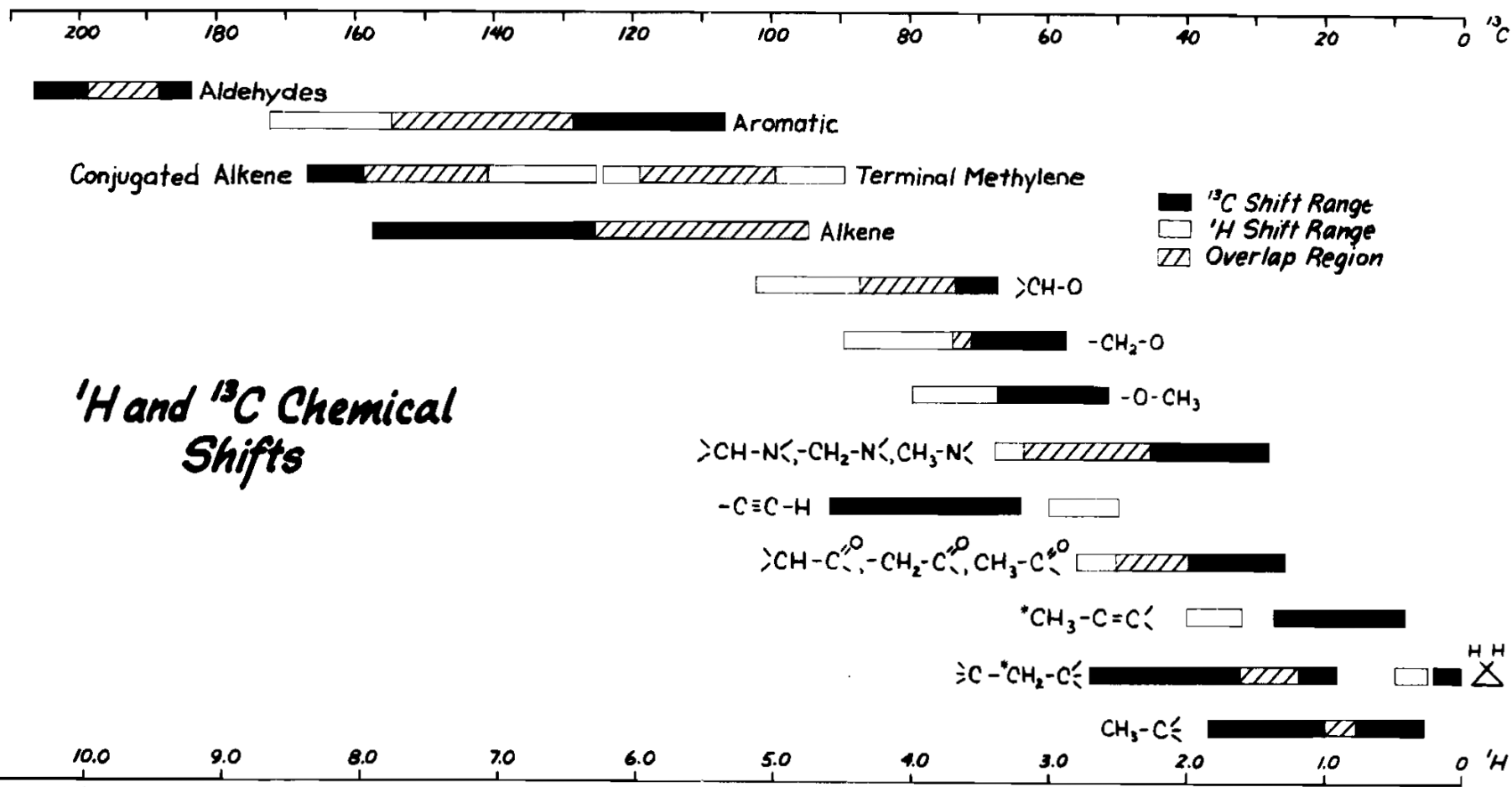Chemically equivalent protons do not split each other's signal

¹H-NMR Spectroscopy

How many signals you expect in 1H-NMR?

What will be the multiplicity of each signal?

^{1}H-NMR Spectroscopy


^{1}H and ^{13}C Chemical Shifts

Legend:
- ■ ^{13}C Shift Range
- □ ^{1}H Shift Range
- ▨ Overlap Region

^{13}C scale (top): 200, 180, 160, 140, 120, 100, 80, 60, 40, 20, 0 ^{13}C

^{1}H scale (bottom): 11.0, 10.0, 9.0, 8.0, 7.0, 6.0, 5.0, 4.0, 3.0, 2.0, 1.0, 0 ^{1}H

Groups shown:
- Aldehydes
- Aromatic
- Conjugated Alkene
- Terminal Methylene
- Alkene
- >CH-O
- -CH$_2$-O
- -O-CH$_3$
- >CH-N<, -CH$_2$-N<, CH$_3$-N<
- -C≡C-H
- >CH-C(=O), -CH$_2$-C(=O), CH$_3$-C(=O)
- *CH$_3$-C=C<
- >C-*CH$_2$-C<
- CH$_3$-C<

¹H-NMR Spectroscopy
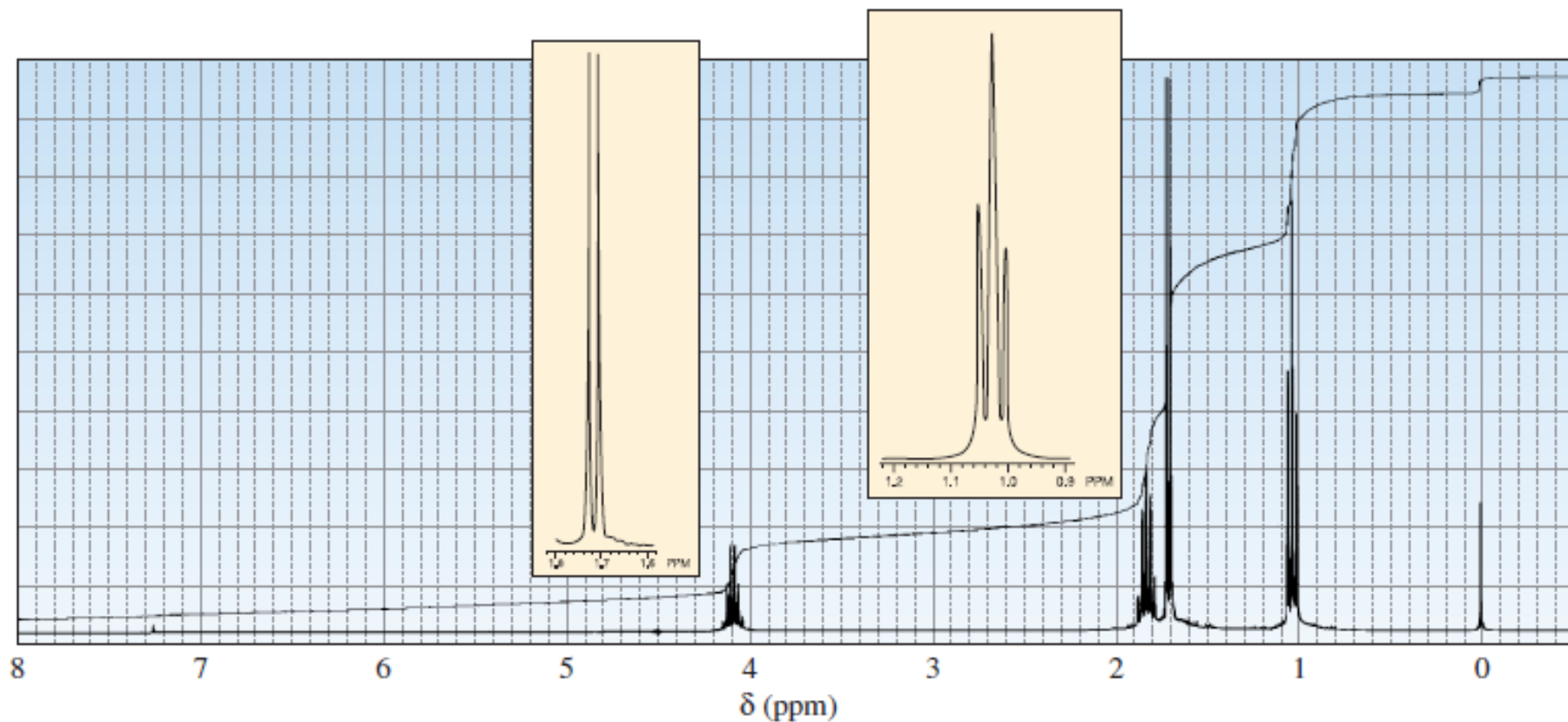
One isomer of coumalic acid has the 1H NMR spectrum 6.41 (1H, d), 7.82 (1H, dd), 8.51 (1H, d). which isomer is it?
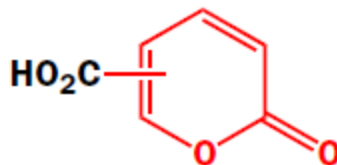
^{1}H-NMR Spectroscopy

The ^{1}H-NMR spectra of one isomers with molecular formula C_4H_9Br is shown here. ^{13}C-NMR of that isomer give four peaks. What is the molecular structure of that isomer ?

a.

1.2 1.1 1.0 0.9 PPM

5.8 5.7 5.6 PPM

8   7   6   5   4   3   2   1   0

δ (ppm)

Looking forward

**End Sem Examination
on
All Topics Discussed**