NUCLEAR MAGNETIC RESONANCE SPECTROSCOPY

Origin of Spectra

Theory All nuclei possess charge and mass. However, those with either an odd mass number or an odd atomic number also possess spin and have angular momentum.

examples $^{1}_{1}H$ $^{2}_{1}H$ $^{13}_{6}C$ $^{14}_{7}N$ $^{17}_{8}O$ $^{19}_{9}F$ $^{31}_{15}P$ possess spin

but $^{12}_{6}C$ $^{16}_{8}O$ do not

A nucleus with spin can be detected by nuclear magnetic resonance (nmr) spectroscopy.

A spinning nucleus such as ^{1}H behaves as a spinning charge and generates a magnetic field. It can be likened to a bar magnet.

When placed in an externally applied field it can align with, or against, the field.

β — aligned against field

$\Delta E = h\upsilon$

α — aligned with field
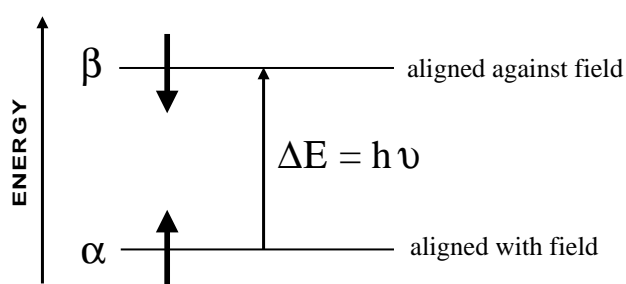
The energy difference between the two states (ΔE) depends on the applied field.

The sample is placed in the field of a large electromagnet and a radio-frequency (RF) field is applied. The magnetic field is increased and the excitation or "flipping" of nuclei from one orientation to another is detected as an induced voltage resulting from the absorption of energy from the RF field.

The basic arrangement of an nmr spectrometer

Radiofrequency oscillator

Ammeter

H_o ⟶
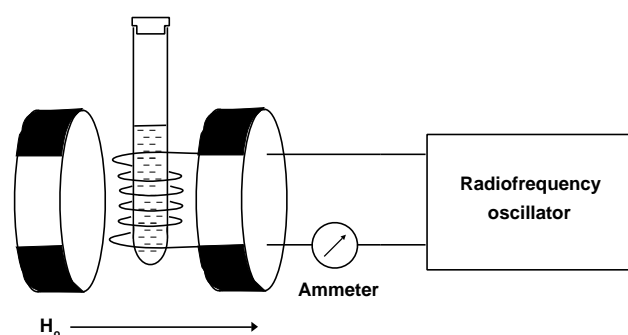
An nmr spectrum is the plot of the induced voltage against the sweep of the field. The area under a peak is proportional to the number of nuclei "flipping"

Other
uses NMR spectroscopy is the same technology as that used in **MRI (magnetic resonance imaging)** to obtain diagnostic information about internal structures in body scanners.

INTERPRETATION OF PROTON NMR SPECTRA

**Introduction** Spectra provide information about the structure of organic molecules from the ...

- number of different signals in the spectrum
- position of the signals (chemical shift)
- splitting pattern of the signals
- intensity of the signals

Running spectra

- a liquid sample is placed in a long thin tube which spins in a magnetic field
- solids are **dissolved in solvents which won't affect the spectrum** - **CDCl₃**
- **tetramethylsilane, (CH₃)₄Si**, is added to provide a reference signal
- the spectrum can be 'integrated' to find the relative peak heights

TMS

- it produces a single intense peak
- signal is just outside the range shown by most protons
- it is inert, non-toxic and has a low boiling point
  it can be distilled off if required

$$CH_3 - \underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{Si}} - CH_3$$
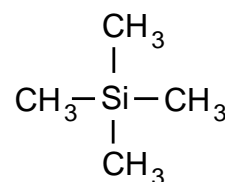
TETRAMETHYLSILANE

Chemical shift

- each proton type is said to be **chemically shifted** relative to a standard
- the chemical shift is the difference between the field strength at which it absorbs and the field strength at which TMS protons absorb
- the delta (δ) scale is widely used as a means of reporting chemical shifts

$$\delta \quad = \quad \frac{\text{Observed chemical shift (Hz) x } 10^6}{\text{Spectrometer frequency (Hz)}} \quad \text{ppm} \quad \text{(parts per million)}$$

- the chemical shift of a proton is constant under the same conditions
- the **TMS** peak is assigned a value of ZERO (δ = 0.00)
- all peaks in the spectrum are related to it and reported in parts per million
- H's near to an electronegative species are shifted "downfield" to higher δ values

Approximate chemical shifts

individual values depend on the environment
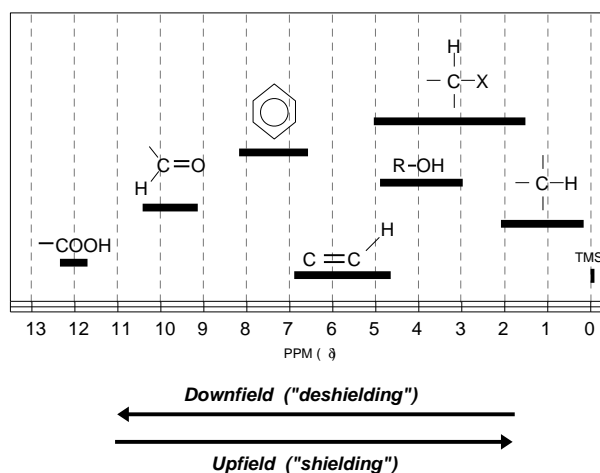
Multiplicity This occurs because the spin of one nucleus affects that of a **chemically different nucleus on an adjacent atom**.

- also known as coupling or spin-spin splitting
- low resolution nmr gives 1 peak for each chemically different group of protons
- high resolution nmr gives more complex signals - doublets, triplets, quartets...
- the signal produced indicates the number of protons on adjacent carbon atoms

No. of peaks = number of H's on adjacent chemically different atoms + 1

Ratio of peak sizes for	2 peaks	"doublet"	1:1
	3 peaks	"triplet"	1:2:1
	4 peaks	"quartet"	1:3:3:1
	5 peaks	"quintet"	1:4:6:4:1

Theory Splitting patterns are worked out by considering the effect **adjacent, chemically different protons** have on another signal in a given environment. The spin of the proton producing the signal is affected by each of the two forms of the adjacent proton. One orientation augments/enhances its field and the other opposes/reduces it. Splitting patterns can be worked out by calculating the various **possible combinations** of alignment of adjacent protons.

1 adjacent H can be aligned either with (α) or against (β) the field   *Fig. 1*
only two equally probable possibilities
the signal is split into **2 peaks** of **equal intensity**

2 adjacent H's more possible combinations - signal is more complex   *Fig. 2*
get **3 peaks** in the ratio **1 : 2 : 1**

3 adjacent H's even more possible combinations   *Fig. 3*
get **4 peaks** in the ratio **1 : 3 : 3 : 1**

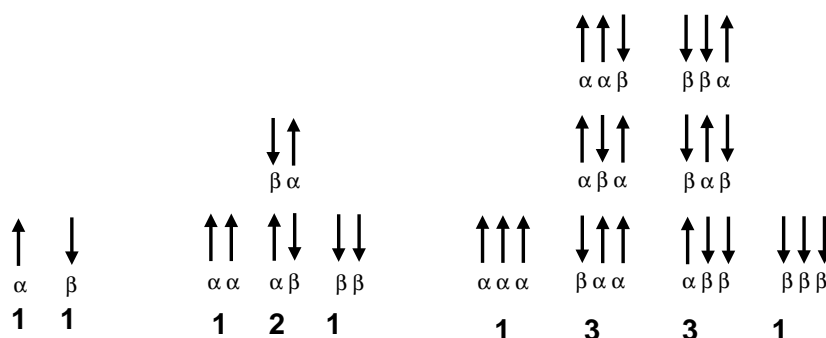|		
↑↑↓	↓↓↑	
α α β	β β α	
↓↑	↑↓↑	↓↑↓
β α	α β α	β α β
↑ ↓	↑↑ ↑↓ ↓↓	↑↑↑ ↓↑↑ ↑↓↓ ↓↓↓
α β	α α α β β β	α α α β α α α β β β β β
1 1	**1 2 1**	**1 3 3 1**

*Fig. 1*   *Fig. 2*   *Fig. 3*

> *Q.1* *Explain the splitting pattern when there are four adjacent protons.*

Chemically different?   Coupling only **takes place with**   chemically different protons

It **DOES NOT take place with**   chemically similar protons   *or*
H atoms on OH groups

To see if a hydrogen is chemically different you need to look at the whole structure of the molecule, not just the neighbouring atom(s).
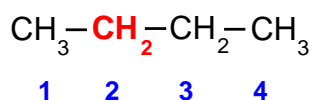
Example 1 $CH_3 - \textbf{CH}_2 - CH_2 - CH_3$ **two sets of signals**
1   2   3   4
A triplet due to the CH_3 groups - 2 adjacent H's +1
A quartet due to the CH_2 groups - 3 adjacent H's +1

• the signal due to the H's on carbon 2 is not a hextet   (5 + 1 = 6)
• the 2 H's on carbon 3 are CHEMICALLY IDENTICAL to those on carbon 2
• **chemically identical hydrogens do not affect the splitting pattern**

Example 2

$$CH_2$$
$$CH_2 \qquad CH_2$$
$$CH_2 \qquad CH_2$$
$$CH_2$$
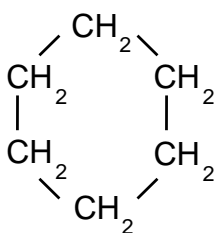
one signal - a singlet

• all the hydrogen atoms are chemically equivalent
• there are no chemically equivalent hydrogens on adjacent atoms
• the signal will be a singlet - 0 + 1 = 1
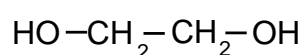
Example 3 $HO - CH_2 - CH_2 - OH$ **two signals**   - singlet due to the CH_2 groups
- singlet due to the OH groups

• **signals due to H's on OH groups are always singlets**
• the H's on the CH_2 give rise to a singlet because...
• the H atoms on the adjacent CH_2 are chemically equivalent so don't and
H's on adjacent OH groups do not couple

Special note   **Signals for the H in an O-H bond**   • unaffected by H's on adjacent atoms
• are not split *(see later)*

A spectrum of a typical alcohol (ethanol) is shown on the next page. One would expect a triplet signal (3 peaks) for the H in O-H but there is only one.
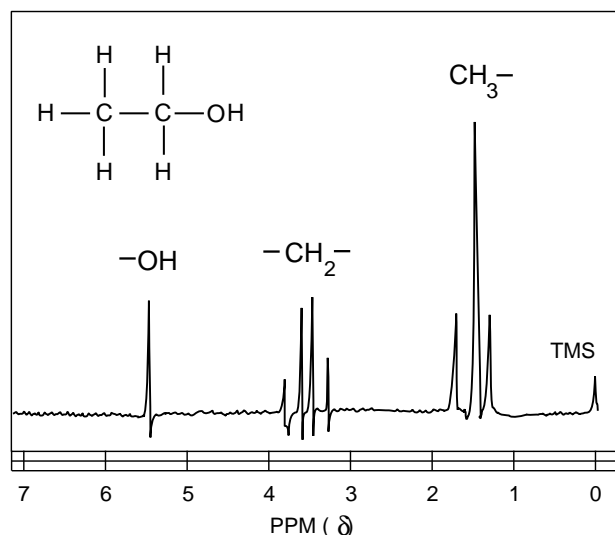
Q.2   *Why are the signals due to the CH₂ hydrogens in BrCH₂CH₂Br singlets not triplets ?*

Integration
- the area under a signal is proportional to the number of hydrogen atoms present
- is achieved using an integration device which scans the peaks
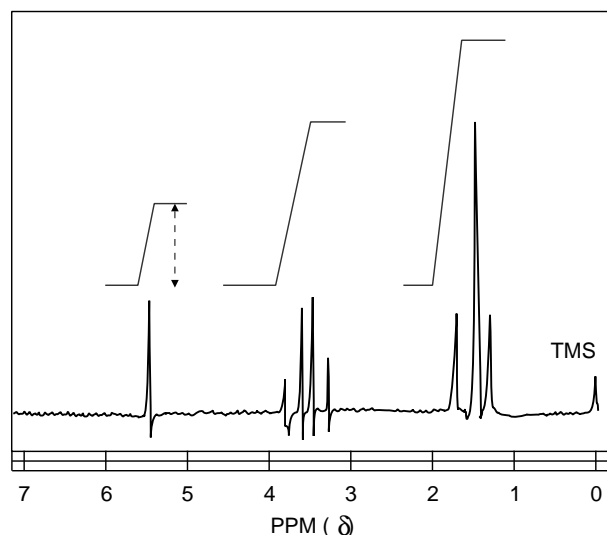- lines on the spectrum show the **relative abundance** of each hydrogen type

By measuring the distances between the integration lines (dotted line on the spectrum) one can work out a simple ratio between the various types of hydrogen.
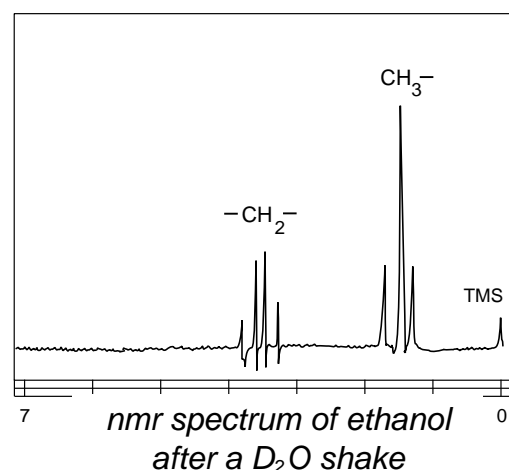
The nmr spectrum of ethanol

(i) before integration   *(ii) after integration*

Q.3 *Measure the ratio of the heights of the integration lines in the ethanol spectrum. Does it correspond to the actual ratio of protons in the structure ?*

D_2O shake The signal due any **hydroxyl (OH)** hydrogen is seen as a **singlet**; **no splitting**
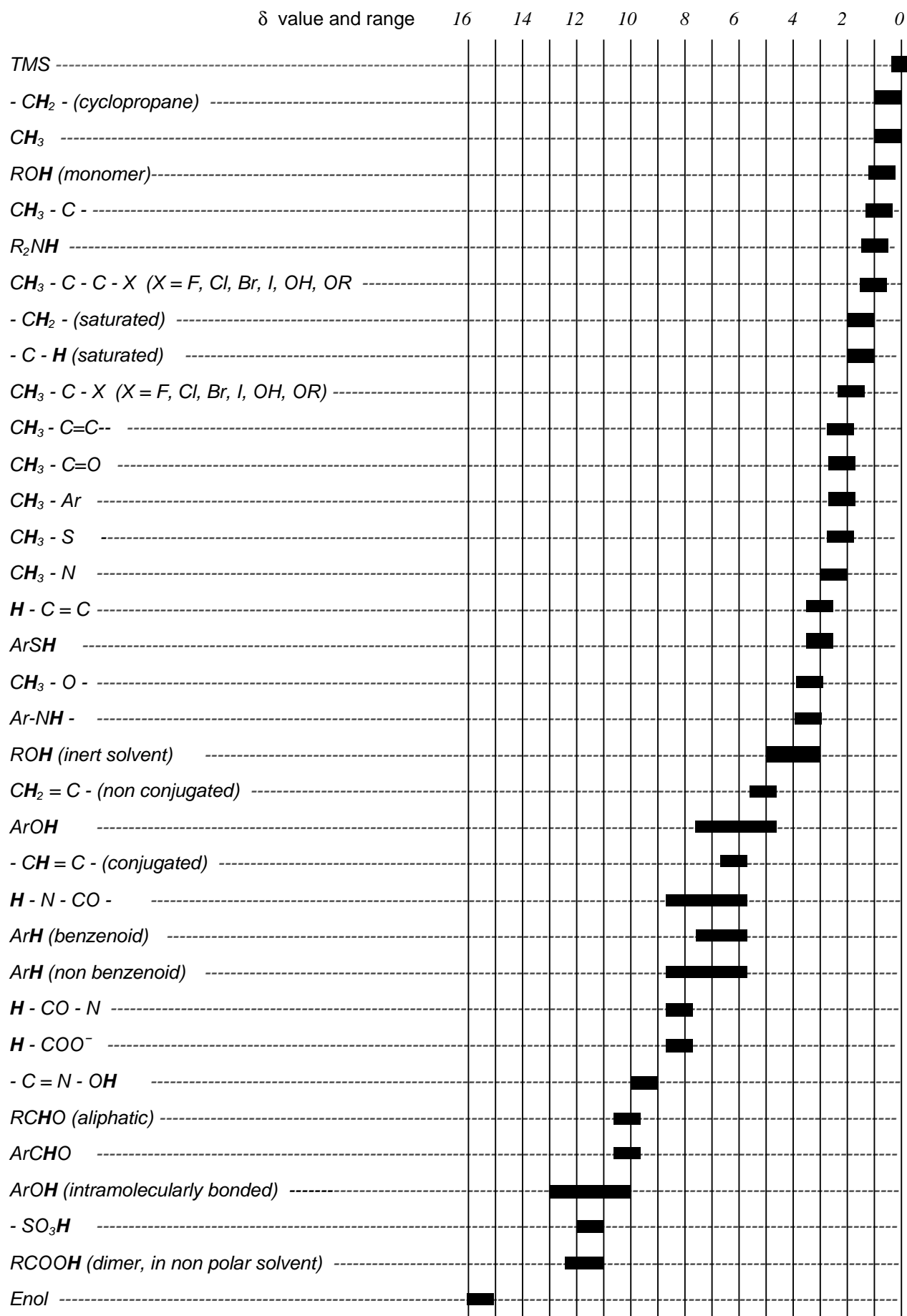
This arises because proton on the OH, rapidly exchanges with protons on other molecules and is not attached to any particular oxygen long enough to register a splitting signal.

It is possible to exchange the H for deuterium, ^2H or D. The usual source is deuterium oxide, D_2O , a form of water.
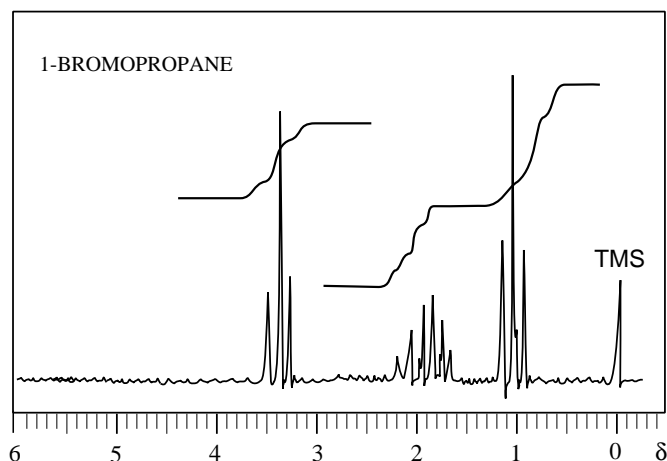
Deuterium doesn't exhibit nuclear magnetic resonance under the conditions used for proton nmr so the signal is removed to another part of the spectrum.

nmr spectrum of ethanol after a D_2O shake

SOME TYPICAL PROTON CHEMICAL SHIFTS

δ value and range 16 14 12 10 8 6 4 2 0

- TMS
- *CH₂* - (cyclopropane)
- *CH₃*
- *ROH (monomer)*
- *CH₃ - C -*
- *R₂NH*
- *CH₃ - C - C - X (X = F, Cl, Br, I, OH, OR*
- *CH₂* - (saturated)
- *C - H (saturated)*
- *CH₃ - C - X (X = F, Cl, Br, I, OH, OR)*
- *CH₃ - C=C--*
- *CH₃ - C=O*
- *CH₃ - Ar*
- *CH₃ - S*
- *CH₃ - N*
- *H - C = C*
- *ArSH*
- *CH₃ - O -*
- *Ar-NH -*
- *ROH (inert solvent)*
- *CH₂ = C - (non conjugated)*
- *ArOH*
- *CH = C - (conjugated)*
- *H - N - CO -*
- *ArH (benzenoid)*
- *ArH (non benzenoid)*
- *H - CO - N*
- *H - COO⁻*
- *C = N - OH*
- *RCHO (aliphatic)*
- *ArCHO*
- *ArOH (intramolecularly bonded)*
- *SO₃H*
- *RCOOH (dimer, in non polar solvent)*
- *Enol*

INTERPRETING THE NMR SPECTRUM OF 1-BROMOPROPANE

1-BROMOPROPANE

TMS

Analysis

Peaks　　　There are three different signals so there are three chemically different protons.

Position　　The further the signals are shifted from TMS signal, the nearer they are to the Br.

Splitting　　The signals include a　triplet　$(\delta = 1.0)$
　　　　　　　　　　　　　　　　　sextet　$(\delta = 1.8)$
　　　　　　　　　　　　　　　　　triplet　$(\delta = 3.4)$

$$H-\overset{\overset{\displaystyle H}{|}}{\underset{\underset{\displaystyle H}{|}}{C}}_{1}-\overset{\overset{\displaystyle H}{|}}{\underset{\underset{\displaystyle H}{|}}{C}}_{2}-\overset{\overset{\displaystyle H}{|}}{\underset{\underset{\displaystyle H}{|}}{C}}_{3}-Br$$

The signals due to the protons attached to carbon ...

C^1　triplet　$(\delta = 1.0)$　coupled to the two protons on carbon C^2　　　　(2+1 = 3)
C^2　sextet　$(\delta = 1.8)$　coupled to five protons on carbons C^1 and C^3　(5+1 = 6)
C^3　triplet　$(\delta = 3.4)$　coupled to the two protons on carbon C^2　　　　(2+1 = 3)

Integration　The integration lines show that the ratio of protons is 2:2:3

**Summary**　　An nmr spectrum provides several types of information :-

- number of signal groups　-　the number of different proton environments
- chemical shift　　　　　　-　the general environment of the protons
- multiplicity　　　　　　　-　how many protons are on adjacent atoms
- peak area　　　　　　　　-　the number of protons in each environment

In many cases this information is sufficient to deduce the structure of a molecule.

Q.4　　*What would you expect the spectrum of 2-bromopropane to be like ?*
　　　　Explain your answer in terms of　　*a)　the chemical shift*
　　　　　　　　　　　　　　　　　　　　　b)　the splitting pattern
　　　　　　　　　　　　　　　　　　　　　c)　integration

SAMPLE SPECTRA

C₄H₈O₂

C₄H₈O

**C₃H₆O**

C₃H₆O
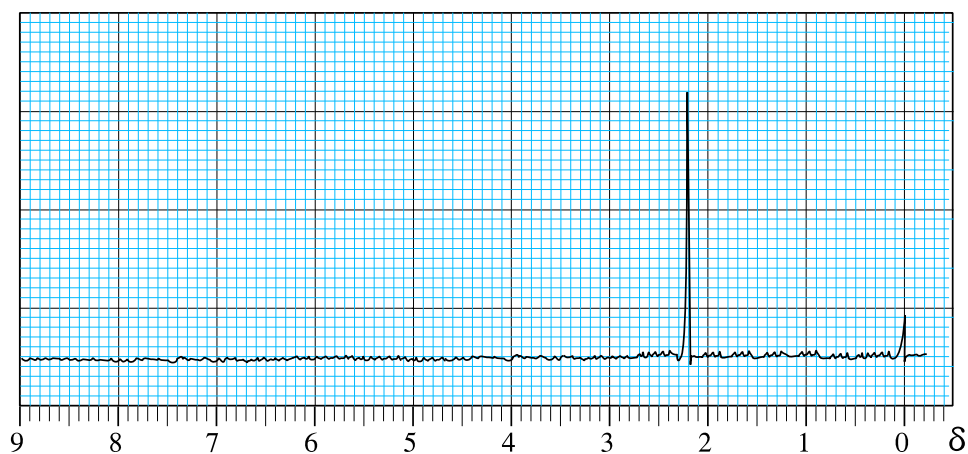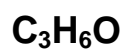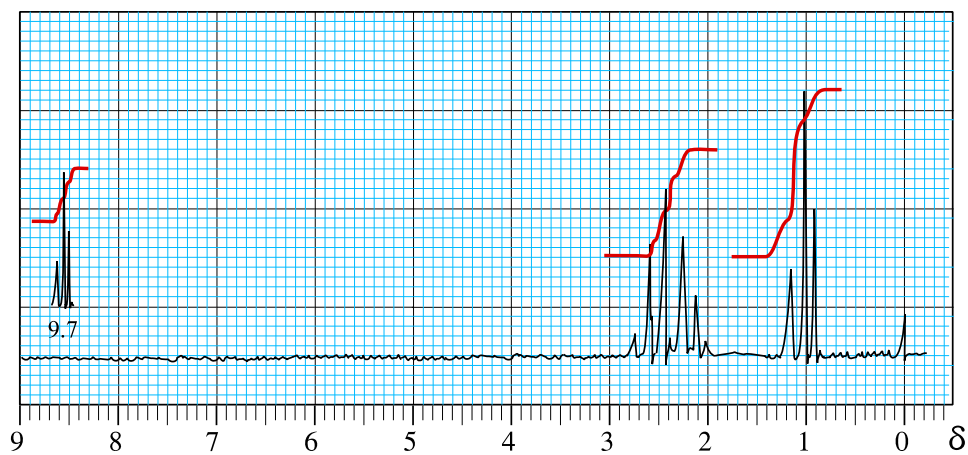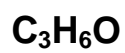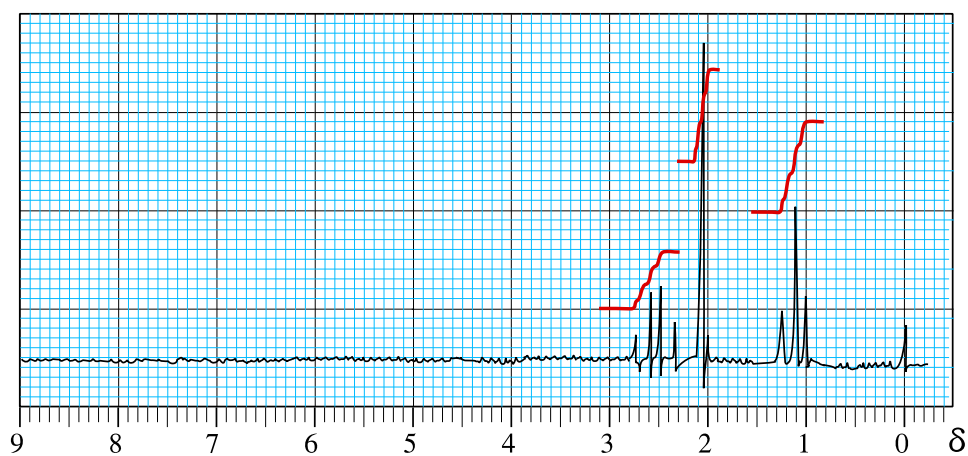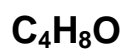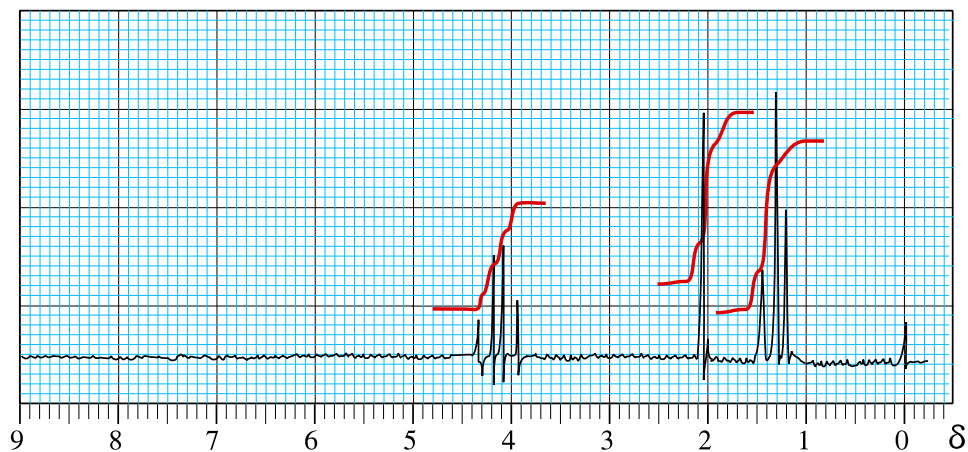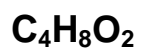
CARBON-13 SPECTRA

Theory   After hydrogen, the most useful atom providing information to organic chemists is carbon-13. Natural carbon contains about 1% of this isotope so the instruments for its detection need to be sensitive and spectra will take longer to record.

Only the chemical shift is important as **each spectrum gives only single lines for each chemically equivalent carbon**. Carbon-13 nmr has wide applications in the study of natural products, biological molecules and polymers.

Type of carbon	Chemical shift, δ ppm
C - **C** (alkanes)	10 - 35
C - C=O	10 - 35
C - Cl or **C** - Br	30 - 70
C - N (amines)	35 - 65
C - OH	50 - 65
C = **C** (alkenes)	115 - 140
aromatic **C's** (benzene rings)	125 - 150
C=O (esters, acids, amides)	160 - 185
C=O (aldehydes, ketones)	190 - 220

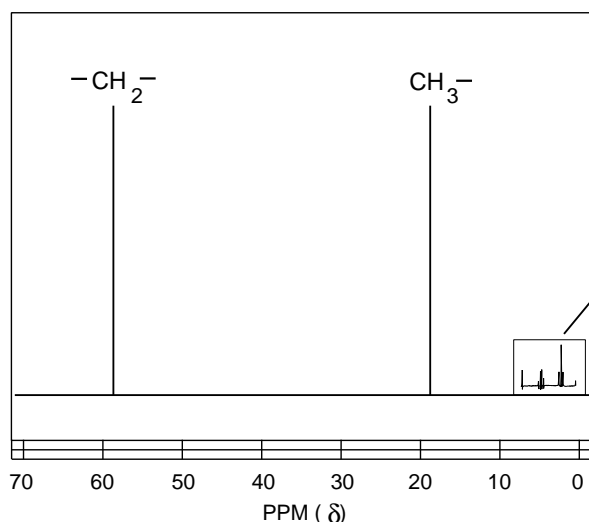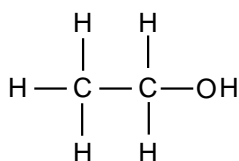*Interpretation for C_3H_7Br*
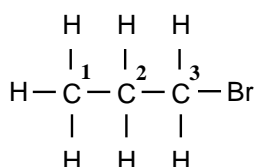
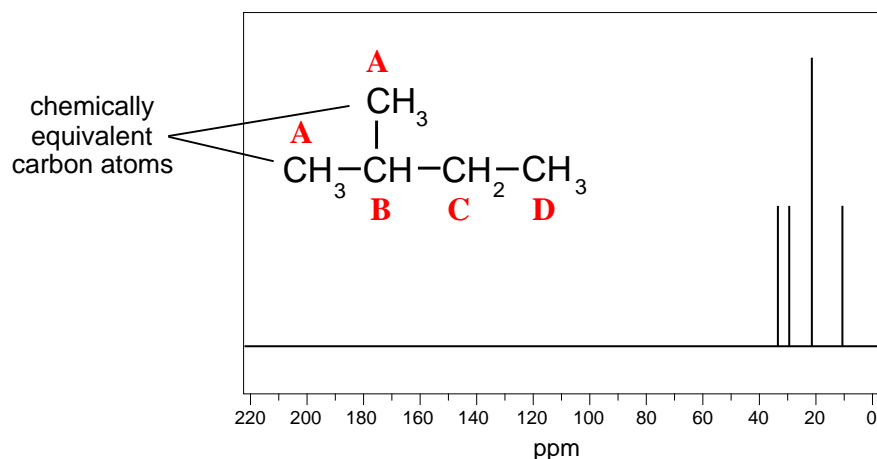**3 peaks**
all three carbons are different
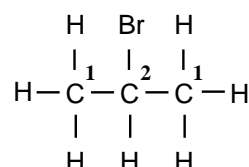
2 peaks
the two outer carbons are similar

C-13 nmr spectrum of ethanol C_2H_5OH

This is where the proton nmr spectrum of ethanol would be on the same scale.

The Carbon-13 spectrum of 2-methylbutane C_5H_{12}

chemically equivalent carbon atoms

$$\underset{\underset{B}{}}{CH_3}-\underset{}{CH}-\underset{\underset{C}{}}{CH_2}-\underset{\underset{D}{}}{CH_3}$$

A CH$_3$ (A)

There are four chemically different carbon atoms in the molecule so there are four peaks in the ^{13}C nmr spectrum.

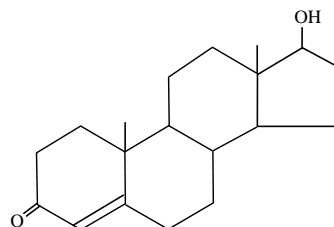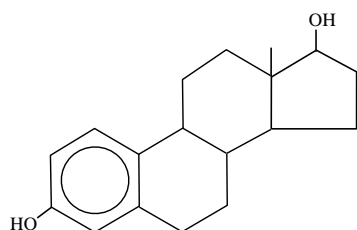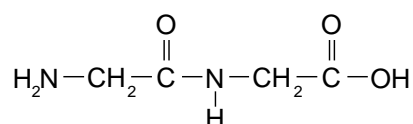**NO SPLITTING WITH ^{13}C**

ONLY ONE PEAK FOR EACH CARBON

220 200 180 160 140 120 100 80 60 40 20 0
ppm

Other isomers of C_5H_{12} pentane $CH_3CH_2CH_2CH_2CH_3$ 3 peaks
2,3-dimethylpropane $(CH_3)_4C$ 2 peaks

SUPPLEMENTARY QUESTIONS

Q.5 (i) *State how many peaks would you expect to see in the carbon-13 spectrum of...*
butane   2-methylpropane   butanal   butanone
pentanal   pentan-2-one   pentan-3-one   ethanol

$$CH_3-CH=CH-\underset{\underset{\underset{CH_3}{|}}{\underset{|}{CH}}}{CH}-\underset{\underset{\underset{CH_3}{|}}{\underset{|}{CH_2}}}{CH}-CH_3$$

$$H_2N-CH_2-\overset{\overset{O}{\|}}{C}-\underset{\underset{H}{|}}{N}-CH_2-\overset{\overset{O}{\|}}{C}-OH$$
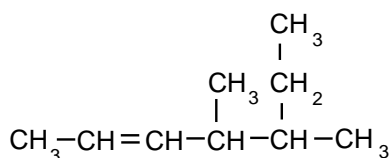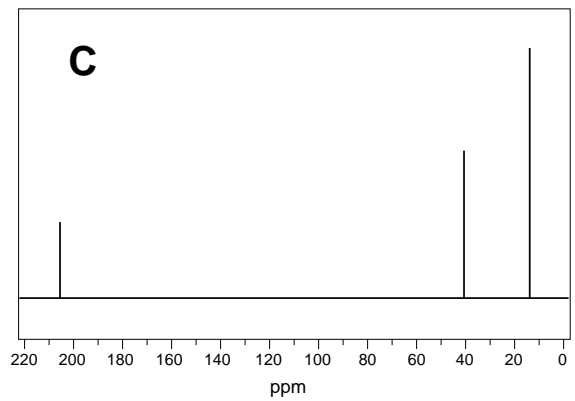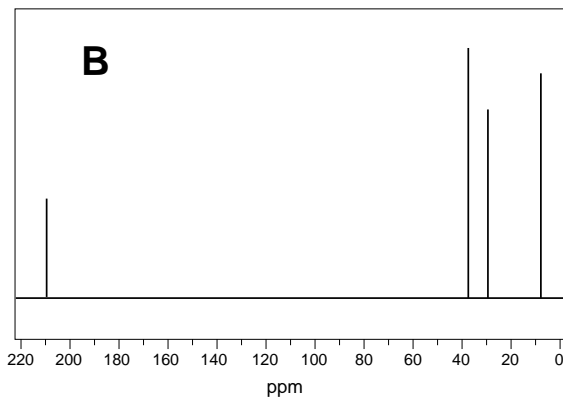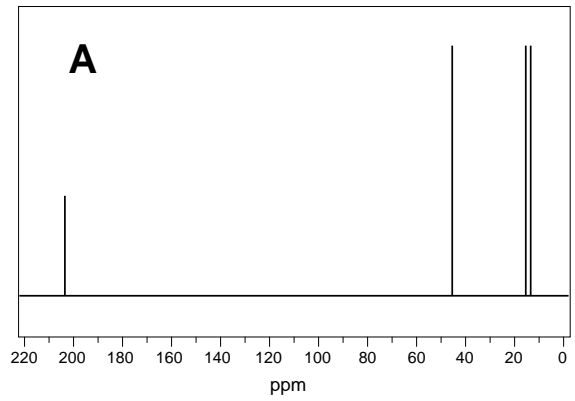
(ii) *State a similarity and a difference between the spectra of...*

a) *butane and 2-methyl propane*

b) *butanal and butanone*

Q.6 *Identify the isomers of C_4H_8O*

A

B

C

Q.7 *Identify the isomers of C_6H_{12}*

X

Y

Z