Analytical Chemistry

Nuclear Magnetic Resonance, NMR

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Magnetic Properties Of ^{1}H

- Nucleus of hydrogen atom has 1 proton.
- Proton of hydrogen atoms spin about an axis.
- This spin is associated with a circulation of electric charge → causing a magnetic field.
- So the **spinning ^{1}H nucleus has a magnetic moment** along the axis of rotation.

- *When put in an ***external*** **magnetic field** the **nuclei tend to turn to 2 orientation :**

1) nuclear magnet is **aligned** with the external field - a preferred orientation.

2) nuclear magnet **opposing** the external field - less favoured orientation

Magnetic Properties Of ^{1}H

- The only **two orientations** allowed for nuclei such as ^{1}H, which have a **nuclear spin of ½ a unit**

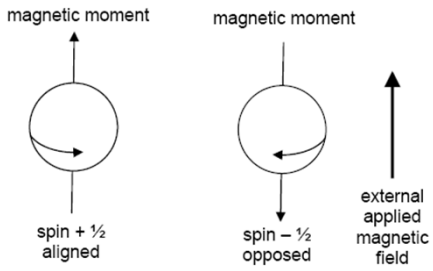
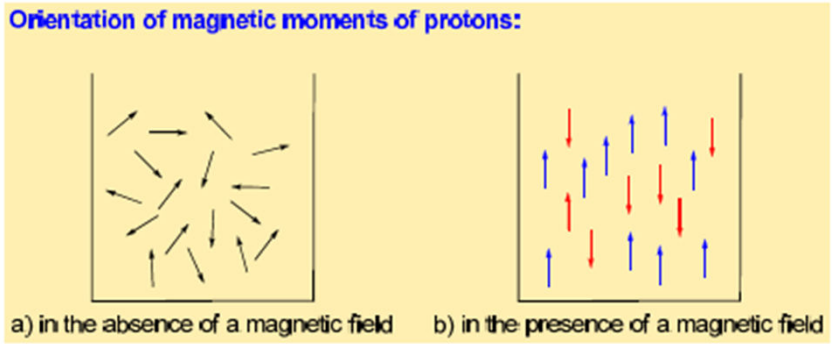


Figure 2.5 - nuclear spin

Magnetic Properties Of ^{1}H



Taken from NMR spectroscopy, Lecture 1, Dr Lim Kuan Hon, University of Nothingham (M'sia)

Magnetic Properties Of ^1H

- In the **absence of an applied** field, the spin states of a given nucleus are of equal energy.
- When **external magnetic field** applied, the opposite **spin states have different** energies and the two spin states **occupy two different energy levels**.

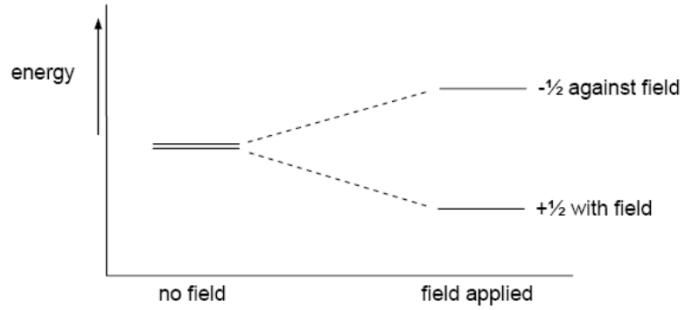
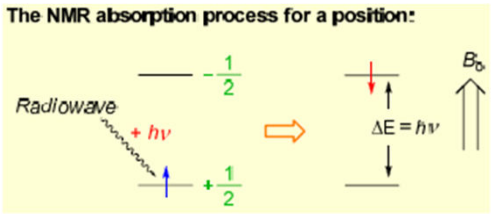


Figure 2.6 – spin states in an external magnetic field

Magnetic Properties Of ^1H

- The phenomenon of **nuclear magnetic resonance occurs when nuclei aligned with the applied field absorb energy** (ΔE in Figure 2.6) and **change their spin orientation with respect to the field**.



Taken from NMR spectroscopy, Lecture 1, Dr Lim Kuan Hon, University of Nothingham (M'sia)

- The absorption of energy (*radio wave) which results in the* excitation of the nucleus from the lower to higher energy level is called **resonance**.
- Energy difference between the two spin states is **related to the frequency of electromagnetic radiation** by the Planck equation:

$$\text{energy absorbed} = \Delta E = hf$$

The NMR spectrometer

- a liquid sample is placed in a tube which spins in a magnetic field
- Samples are **dissolved in solvents** which won't affect the spectrum - CCl_4, $CDCl_3$, D_2O
- **TMS, tetramethylsilane, $(CH_3)_4Si$**,(volatile and inert) is added to provide a **reference signal.**
- It produces a strong singlet peak at a higher field.

The NMR spectrometer

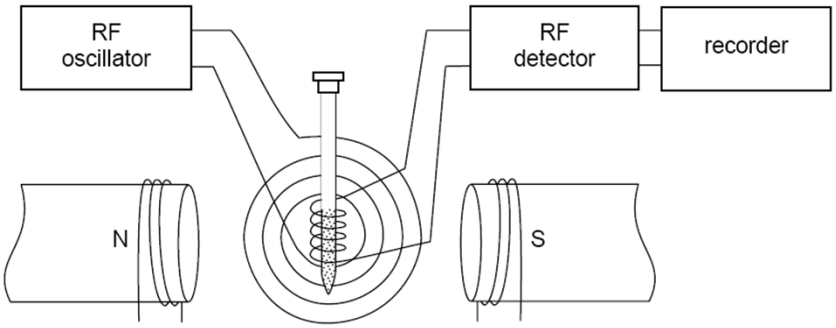


Figure 2.7 – the NMR spectrometer

The NMR spectrometer

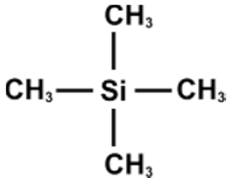
- The sample is placed in the field of a large electromagnet and a radio-frequency (RF) field is applied.
- The RF field is applied → "flipping" of nuclei (excitation) is detected as an induced voltage resulting from the absorption of energy from the RF field.
- when the spectrum has been run, it can be integrated to find the relative peak areas
- spectrometers are now linked to computers to analyse data and store information
- An nmr spectrum is the plot of the induced voltage against the sweep of the field.

TETRAMETHYLSILANE - TMS

PROVIDES THE REFERENCE SIGNAL

- non-toxic liquid - SAFE TO USE
- inert - DOESN'T REACT WITH COMPOUND BEING ANALYSED
- has a low boiling point - CAN BE DISTILLED OFF AND USED AGAIN
- all the hydrogen atoms are chemically equivalent - PRODUCES A SINGLE PEAK
- twelve hydrogens so it produces an intense peak - DON'T NEED TO USE MUCH
- signal is outside the range shown by most protons - WON'T OBSCURE MAIN SIGNALS
- given the chemical shift of $\delta = 0$
- the position of all other signals is measured relative to TMS

The molecule contains four methyl groups attached to a silicon atom in a tetrahedral arrangement. All the hydrogen atoms are chemically equivalent.



The ^{1}H NMR spectra of organic compounds

- Frequency at which a proton absorbs radiation depends on the other atoms in the molecule (different chemical and electrical environment.
- Even in a *constant external* field, protons in **different chemical environments** within a molecule **absorb** at **different frequencies**, because the local magnetic field they experience are different.
- Local magnetic field depends on the electrical and magnetic environment around them.

The ^{1}H NMR spectra of organic compounds

- Electrons pairs spin in opposite directions.
- When a molecule is placed in an external field, the **electron pairs rotate in their orbits** → producing a magnetic field (**induced field**) which **opposes** the **external field**.
- The induced field **'shield' nearby protons from the external field**.
- Therefore **reduces the frequency of the energy absorbed.**

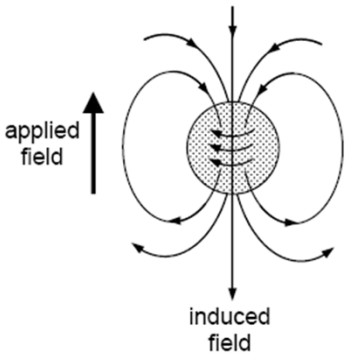


Figure 2.8 – shielding

- Each proton is in a **different chemical environment** will have a **different** amount of electronic **shielding** → a **different resonance frequency**.
- The **resonance frequency** at which a nucleus is able to absorb energy, is known as the **chemical shift.**

Chemical Shift

- An NMR spectrum consists of a **graph of absorbance chemical shift** (symbol δ).
- The chemical shift of a proton is the difference between its absorption frequency and that of TMS, measured in part per million (ppm).

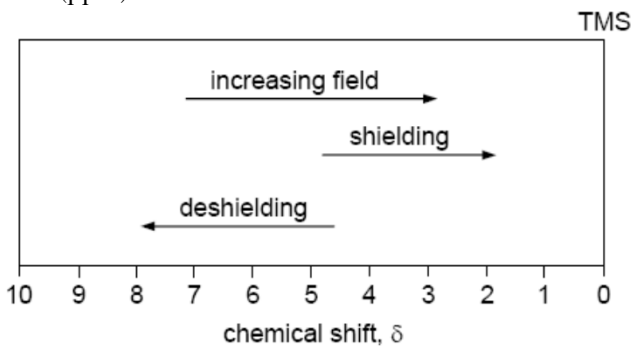


Figure 2.10 – chemical shift

The ^{1}H NMR spectra of organic compounds (shielding)

- Shielding depends on electron density.
- Proton **near an electronegative atom** → **bonding electrons are drawn away** from the proton **to the electronegative atom**.
- The **proton is less shielded** from the external magnetic field, and hence it **absorbs radiation at a higher frequency** (lower field, higher δ value).

The ^{1}H NMR spectra of organic compounds

- For proton attached to a **benzene ring** → **delocalised π electrons in the ring can create a strong diamagnetic effect, opposing the external field**.
- Hence, ***strengthening*** **the magnetic field within the vicinity of the protons**

The ^{1}H NMR spectra of organic compounds

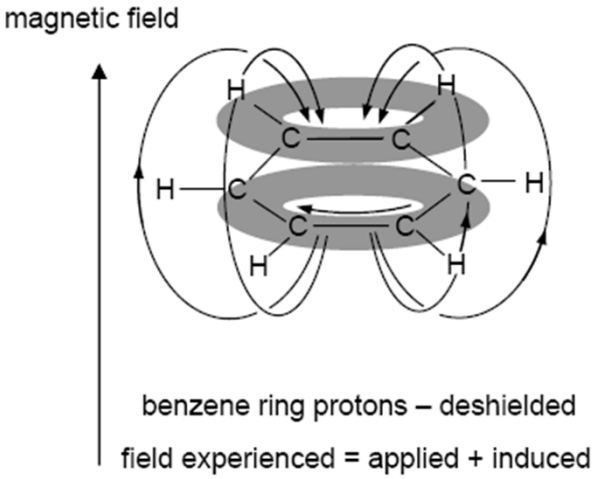
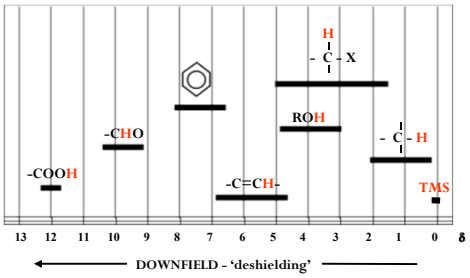


Figure 2.9 – deshielding

Chemical Shift



Approximate chemical shifts

The actual values depend on the environment

Greater electron density will cause greater shielding.

Low resolution ^{1}H NMR spectra of ethanol

- Contains three different absorption peaks at slightly different chemical shift.

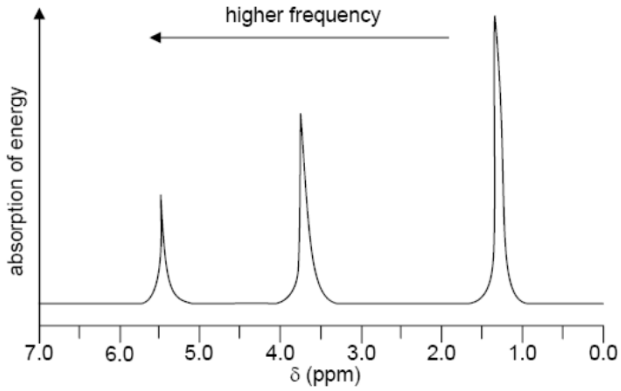


Figure 2.11 – low resolution NMR spectrum of ethanol

Low resolution ^{1}H NMR spectra of ethanol

- These different peaks are the **single -OH proton**, the **two -CH_2- protons** and the **three -CH_3 protons.**
- The protons are in different chemical and electrical environment, giving rise to different chemical shifts.
- The nearer a proton is to the electronegative oxygen atom, the **less shielded** it is from the external magnetic field.
- Area under the peak gives the relative number of equivalent (same environment) 1H responsible for that chemical shift.

High resolution ^{1}H NMR spectra of ethanol

- high-resolution spectrum of ethanol (see Figure 2.12) shows the same three peaks but with different splitting patterns.
- The peak at δ 1.2 is split into three peaks,
- and that at δ 3.7 is split into four.
- This is due to a phenomenon known as **spin-spin coupling**.

High resolution ^{1}H NMR spectra of ethanol

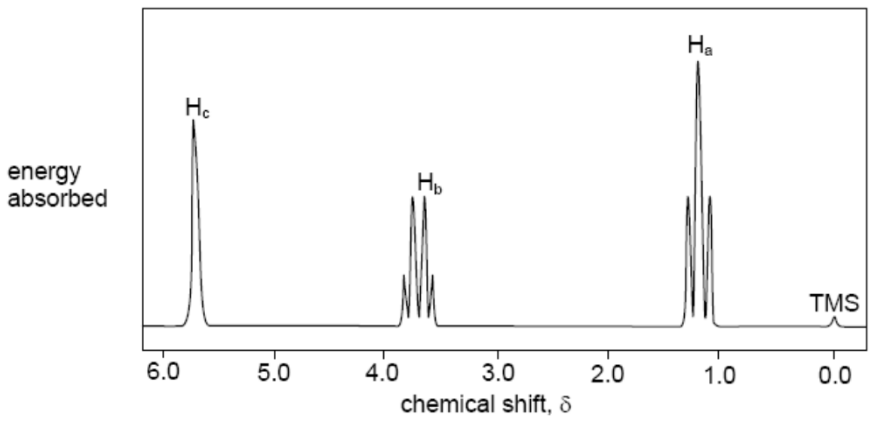
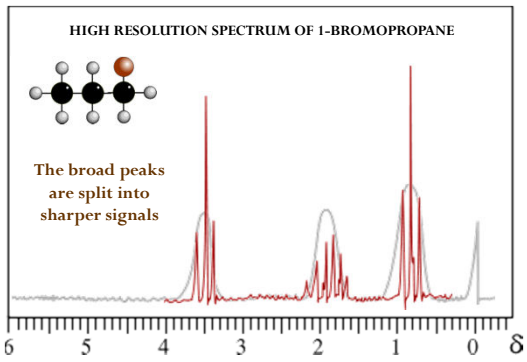


Figure 2.12 – high resolution NMR spectrum of ethanol

LOW RESOLUTION - HIGH RESOLUTION

- low resolution nmr gives 1 peak for each environmentally different group of protons
- high resolution gives more complex signals - doublets, triplets, quartets, multiplets
- the signal produced indicates the number of protons on adjacent carbon atoms



The splitting pattern depends on the number of hydrogen atoms on adjacent atoms

High resolution ^{1}H NMR spectra of ethanol

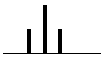
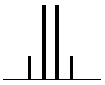
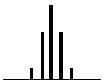
- The general rules governing **splitting patterns** are as follows:

1. Protons in identical chemical environments (e.g. the three H atoms in the -CH_3 group) do not split their own absorption peak.
2. The absorption peak of resonating protons is only split by nearby **protons on the adjacent carbon atom** (3 bonds away).
3. The absorption of protons adjacent to *n* protons is split into (n + 1) peaks.
4. The intensities of the peaks in a multiplet are as in the following table.

MULTIPLICITY

- high resolution gives more complex signals - doublets, triplets, quartets, multiplets
- the signal produced indicates the number of protons on adjacent carbon atoms

Number of peaks = number of chemically different H's on adjacent atoms + 1

1 neighbouring H	2 peaks	"doublet"	1:1	
2 neighbouring H's	3 peaks	"triplet"	1:2:1	
3 neighbouring H's	4 peaks	"quartet"	1:3:3:1	
4 neighbouring H's	5 peaks	"quintet"	1:4:6:4:1	

Signals for the H in an O-H bond are unaffected by hydrogens on adjacent atoms - get a singlet

What about zero adjacent H ?

MULTIPLICITY

PASCAL'STRIANGLE

It is interesting to note the relationship between the successive peak ratios. It follows the pattern found in Pascal's triangle.

Each number in the series is the sum of the two numbers above it in the triangle

What would be the pattern for 6 neighbouring hydrogens?

1
1 1
1 2 1
1 3 3 1
1 4 6 4 1
1 5 10 10 5 1
1 6 15 20 15 6 1

High resolution ^{1}H NMR spectra of ethanol

- You may have noticed that the peak in Figure 2.12 due to the –OH proton is a singlet
- This **splitting does not occur because protons on –OH groups undergo rapid exchange** with each other, and with protons on other –OH groups such as those in water.

$$CH_3CH_2O\boldsymbol{H} + H_2O \rightleftharpoons CH_3CH_2OH + HO\boldsymbol{H}$$

- (The –OH absorption in **ultra-dry** ethanol does in fact appear as a triplet).

High resolution ^{1}H NMR spectra of ethanol

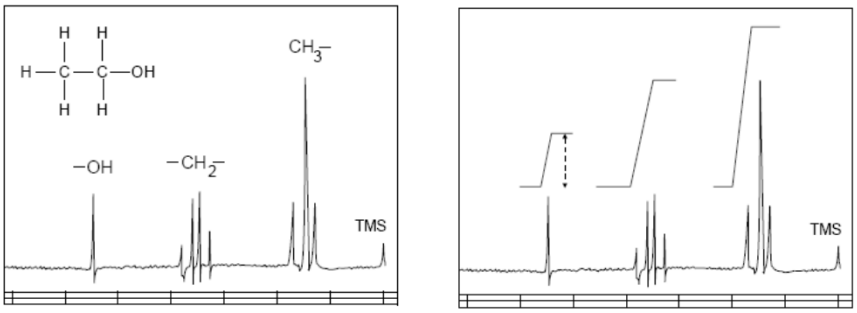
- A useful application of this ready exchange of –OH protons is the **disappearance** of their absorption **peak** when an NMR sample is shaken with $\mathbf{D_2O}$ (D is deuterium, ^{2}H).

$$CH_3CH_2OH + D_2O \rightleftharpoons CH_3CH_2OD + HOD$$

INTEGRATION

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

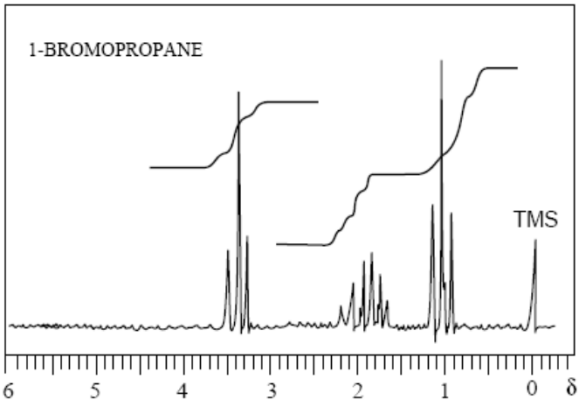
By measuring the distances between the integration lines one can

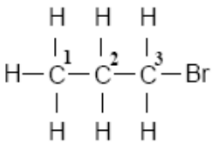


(i) before integration *(ii) after integration*

NOTICETHATTHE O-H SIGNAL IS ONLY A SINGLET

Spectrum of 1-bromopropane





Summary

An nmr spectrum provides several types of information :-

• number of signal groups	tells you ...	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

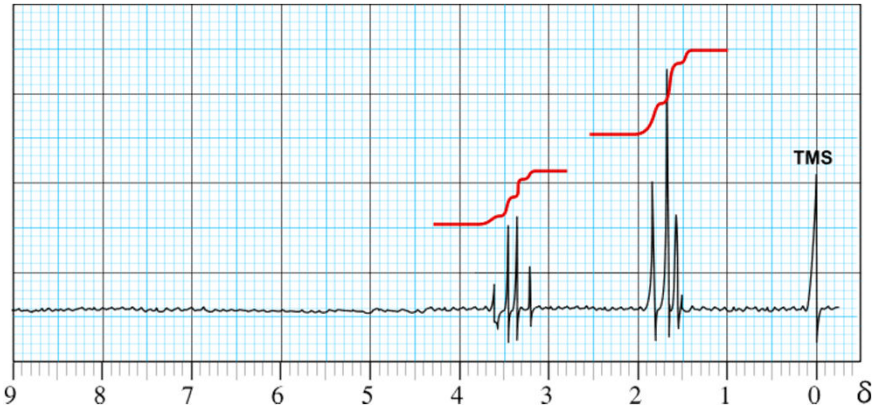
In many cases this information is sufficient to deduce the structure of an organic molecule.

How to interpret 1H-NMR Spectrum

1. Use ∂ values (chemical shifts) to identify environments of equivalent protons at each peak.
2. Look at the integration or relative areas under each peak to determine the number protons at a particular chemical shift.
3. Look at the splitting patterns and apply the (n + 1) rule to see how many protons are on adjacent C atom.
4. Put all the information together to draw the structure.

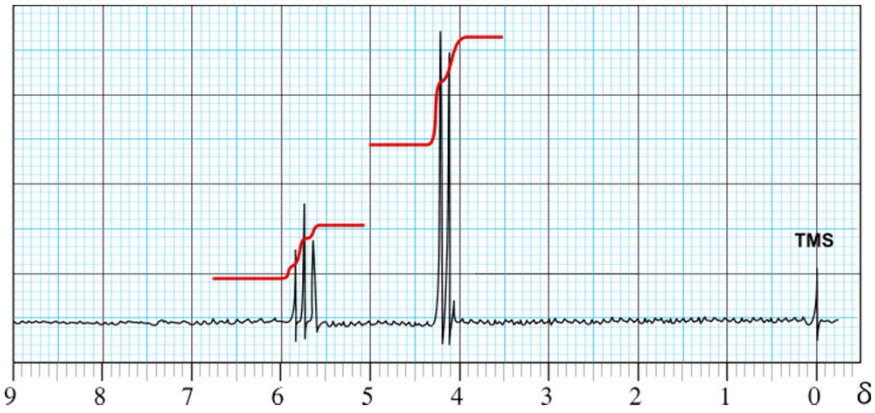
Exercise 1

C_2H_5Br



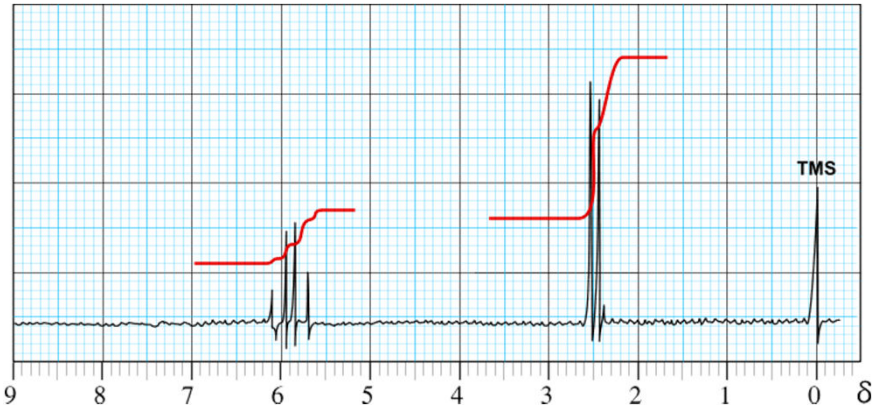
Exercise 2

$C_2H_3Br_3$



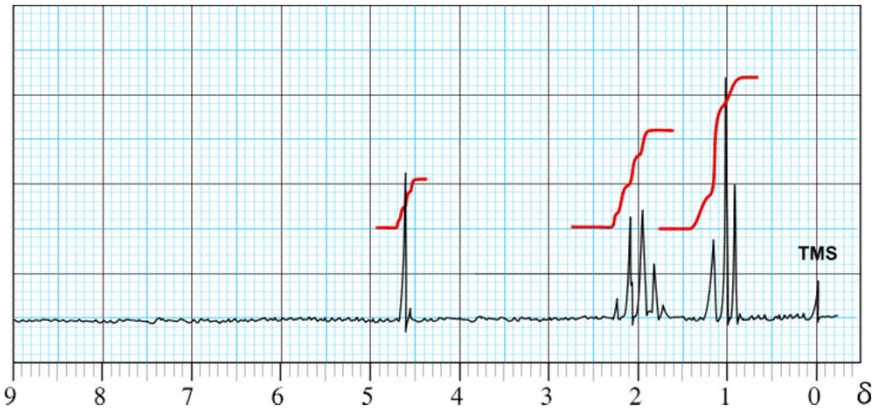
Exercise 3

$C_2H_4Br_2$



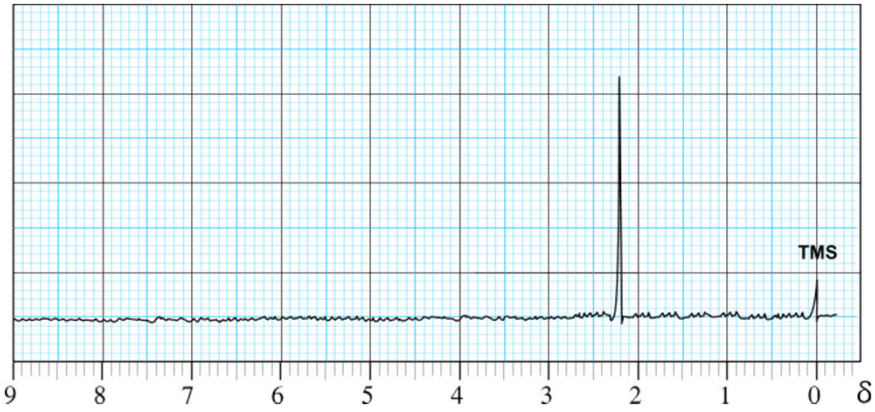
Exercise 4

C_6H_{12}



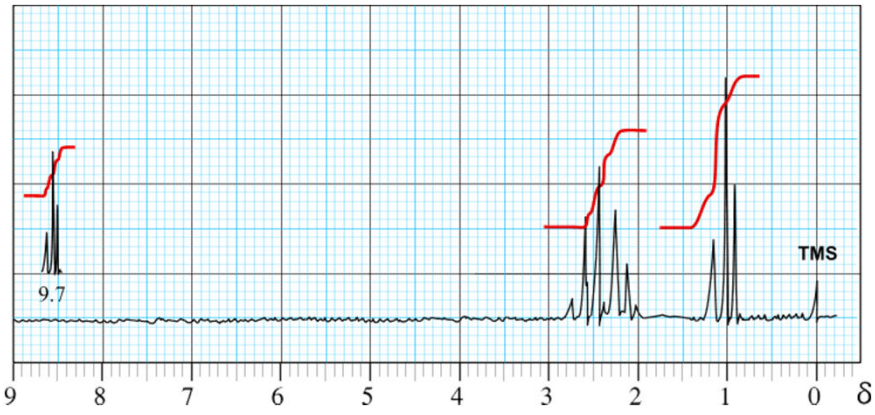
Exercise 5

C_3H_6O



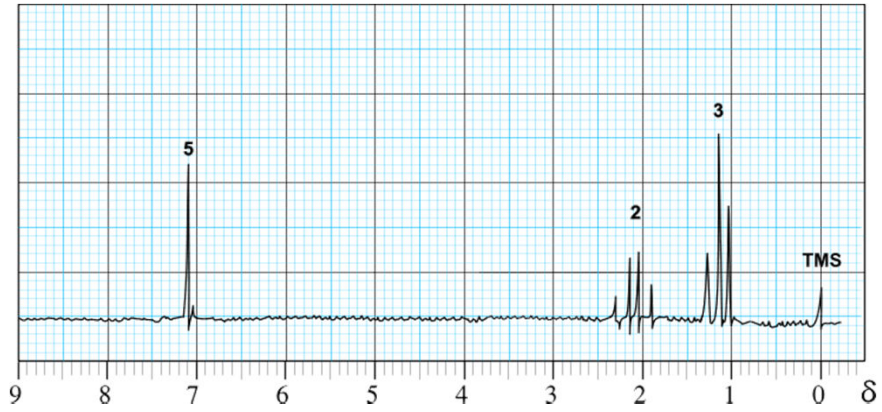
Exercise 6

C_3H_6O



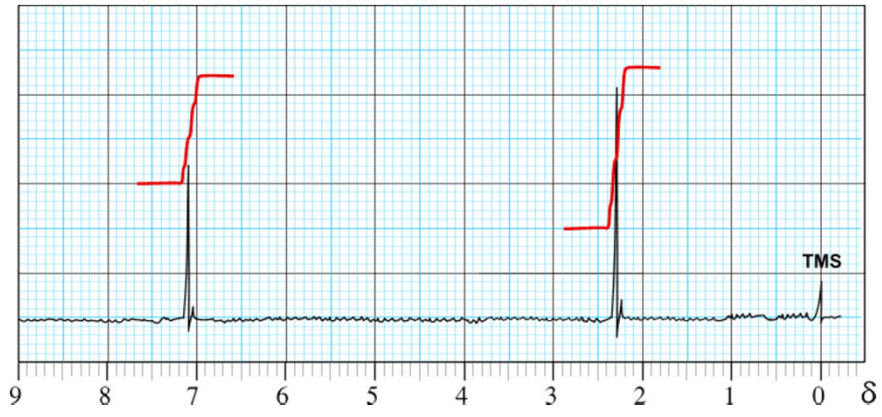
Exercise 7

C_8H_{10}



Exercise 8

C_8H_{10}



Magnetic Resonance Imaging (MRI)

- A patient is placed on a steady table and the part of the body to be scanned (often the head) is immobilised.
- The table is slowly passed through the magnetic field, where a fine beam of UHF radiation is passed through and analysed.
- This shows the ^{1}H absorption pattern of a thin section (about 1 cm thick) of the body.
- The table continues to move gently into the magnetic field, and after each 1 cm another absorption pattern is recorded.
- A typical brain scan containing 20-30 slices takes only 10 minutes to complete.

Magnetic Resonance Imaging (MRI)

- Most of the hydrogen atoms within cells are in water molecules or lipid molecules, and it is the environment of the water molecules that gives an indication of the medical state of the cell.
- MRI is useful in pinpointing brain tumours and sites of injury, and diagnosing hydrocephalus, multiple sclerosis, Alzheimer's and other brain diseases.