OCR A Chemistry A-level

Module 6.3: Analysis

Detailed Notes

6.3.1 Chromatography and Qualitative Analysis

Types of Chromatography

Chromatography is an **analytical technique** used to separate and identify component molecules of a mixture. Separation of the mixture depends on distribution between a **mobile** phase and a **stationary** phase.

Mobile and Stationary Phases

The mobile phase is a fluid that allows molecules to **move over or through** the stationary phase. It can be in the form of a **liquid or a gas** depending on the type of chromatography being carried out. Species that are more soluble in the mobile phase **move further and/or faster** within the mobile phase.

The stationary phase is a substance that has **affinity** to molecules in the mixture being analysed. The **greater the affinity** of a molecule to the stationary phase, the **shorter the distance and/or the slower** it moves within the mobile phase.

Rf Values

An Rf value is a retention factor that is **unique** to each different component molecule in the mixture being analysed. This is because different molecules within the mixture will have **different affinities** for the mobile and stationary phase and so will move at different rates within the mobile phase. It is calculated by comparing the **distance moved by the component molecule to the distance moved by the mobile phase.**

Example:

$$Rf = \frac{\text{Distance moved by molecule}}{\text{Distance moved by solvent}}$$

There are different types of chromatography that use different mobile and stationary phases. This will lead to **different Rf values** for the molecules present. A particular component molecule will have a different Rf value in different **solvents**.

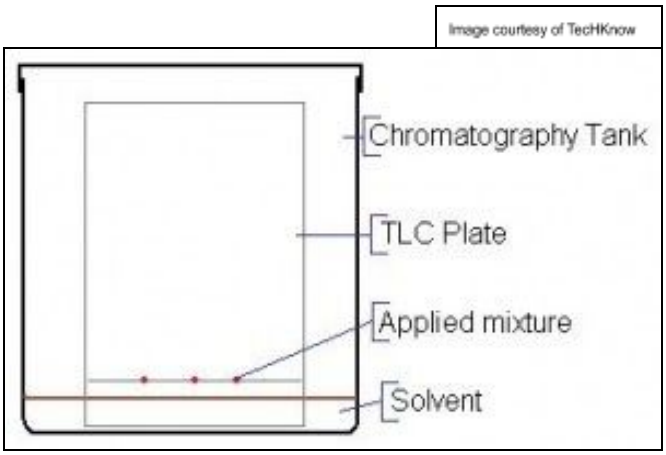
Thin-Layer Chromatography (TLC)

In TLC chromatography, a **metal plate** is coated with a **thin layer of silica** and the sample being analysed is dotted on the plate. These initial samples must be placed above the level of the solvent in the container.

The **solvent** is then allowed to move up the plate, separating the substances within the sample. The plate is taken out of the container and the **solvent front** is marked in pencil when it is roughly 1 cm from the top of the plate. This is the distance that the solvent has traveled - this value is needed for **Rf** value calculations.

The plate is then dried in a fume cupboard to reduce toxic fumes. The chemical traces can then be viewed using a **UV lamp** and the distances travelled can be measured. Alternatively, a **developing agent** can be added, such as **iodine**, to allow the **colourless** traces to be seen by the naked eye.

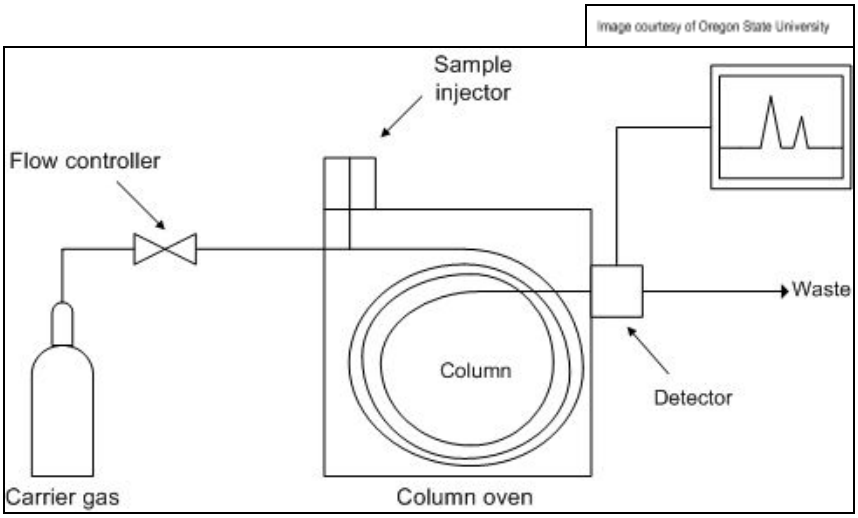
Example: TLC setup



Gas Chromatography (GC)

In gas chromatography, a **thin coiled tube** is packed with a **solid, powdered substance** that acts as the stationary phase. Instead of a solvent, a **high pressure gas** is passed through this tube and acts as the **mobile phase**. This method is used to separate mixtures of **volatile liquids** which are fed into the gas chromatography machine as vapours. The analysis machine **records a retention time** for each component in the mixture, allowing them to be identified.

Example:



Tests for Organic Functional Groups

Data from **NMR**, **element percentage composition**, experimental evidence of the presence of specific **functional groups**, **infrared** and **mass spectroscopy** can be used, often in combination with each other, to predict structures and formulae of organic compounds.

The table below shows the typical reactions of different functional groups and how they can be identified:

Homologous series	Typical reactions	Identification
Alkanes **C-C**	*Combustion* *Electrophilic substitution/free radical substitution* with Br_2 or Cl_2 (forms halogenoalkanes) *Cracking* (forms short chain alkenes and alkanes)	
Alkenes **C=C**	*Electrophilic addition:* - Steam (forms alcohols) - Hydrogen halides (forms halogenoalkanes) - Halogens (forms di-halogenoalkanes) - Hydrogen (forms alkanes) *Oxidation* with H^+/MnO_4^- (forms diols) *Addition polymerisation* (forms polymers) *Combustion*	**React with bromine water:** Decolorises in the presence of C=C.
Haloalkanes **C-F/ C-Cl/ C-Br/ C-I**	*Nucleophilic substitution:* - Hydrolysis (forms alcohols) - Reaction with ethanolic cyanide (forms nitriles) - Reaction with ammonia (forms primary amines) *Elimination* of hydrogen halide using ethanolic hydroxide ions (forms alkenes)	**React with $AgNO_3$(aq), test precipitate with NH_3(aq):** **AgCl** - white ppt soluble in dilute NH_3(aq) **AgBr** - cream ppt soluble in concentrated NH_3(aq) **AgI** - yellow ppt insoluble in NH_3(aq)
Alcohols **-OH**	*Combustion* *Substitution* with halogenating agents (forms halogenoalkanes) *Oxidation* with $H^+/Cr_2O_7^{2-}$ (forms carbonyls and carboxylic acids) *Dehydration* using an acid catalyst (forms alkenes) *Esterification* with carboxylic acids or acyl chlorides	**React with $H^+/Cr_2O_7^{2-}$:** Colour change from **orange** to **green** in the presence of primary and secondary alcohols (no change for tertiary alcohols).

Aldehydes -CHO	*Oxidation* with $H^+/Cr_2O_7^{2-}$ (forms carboxylic acids) *Reduction* using $LiAlH_4$ (forms primary alcohols) *Nucleophilic addition* with HCN (forms hydroxynitriles)	**React with 2,4-DNP**: A yellow-orange precipitate is formed in the presence of a carbonyl group. **React with Tollens' reagent:** A silver mirror is produced if an aldehyde is present. **React with Fehling's reagent:** The blue solution forms a brick red precipitate in the presence of an aldehyde. **React with acidified potassium dichromate(VI):** Orange solution turns green.
Ketones RCOR'	*Reduction* using $LiAlH_4$ (forms secondary alcohols) *Nucleophilic addition* with HCN (forms hydroxynitriles)	**React with 2,4-DNP**: A yellow-orange precipitate is formed in the presence of a carbonyl group.
Carboxylic acids -COOH	Reaction with metals, alkalis or carbonates (forms a salt and inorganic products) *Esterification* with alcohols *Reduction* with $LiAlH_4$ (forms alcohols) Reaction with phosphorus(V) chloride (forms acyl chlorides) *Reduction* with $LiAlH_4$ (forms aldehydes and then primary alcohols)	**Test pH:** pH less than 7 when measured using a pH probe. **React with a carbonate**: Effervescence as CO_2 is formed.
Esters RCOOR'	*Acid hydrolysis* (forms a carboxylic acid and an alcohol) *Alkali hydrolysis* (forms a carboxylate salt and an alcohol)	Generally have distinct sweet smells.
Amines $-NH_2$	Reaction with acids (forms a salt)	
Nitriles C≡N	*Acid hydrolysis* (forms a carboxylic acid and a salt) *Alkaline hydrolysis* (forms a carboxylate salt and ammonia) *Reduction* (forms primary aliphatic amines)	
Arenes $-C_6H_5$	*Electrophilic substitution:* - Halogen (forms chlorobenzene with Cl_2 and bromobenzene with Br_2) - Nitration (forms nitrobenzene) Friedel-Crafts *acylation* and *alkylation* *Hydrogenation* (forms cyclohexane)	

Phenol C_6H_5OH	Reactions with strong bases (not acidic enough to react with carbonates) *Electrophilic substitution:* - Bromination using Br_2 (forms bromophenol)	**Test pH:** Weak acidity when tested with a pH probe. **React with a carbonate:** No reaction observed.
Acyl chlorides -COCl	*Hydrolysis* with water (forms carboxylic acids and HCl) *Hydrolysis* with sodium hydroxide (forms a carboxylate salt and water) *Esterification* with alcohols or phenol Reaction with ammonia (forms an amide and HCl) Reactions with primary amines (forms an N-substituted amide)	
Amides $-CONH_2$	*Acid hydrolysis* (forms a carboxylic acid and ammonium ions) *Alkali hydrolysis* (forms a carboxylate salt and ammonia or an amine) *Reduction* using $LiAlH_4$ (forms a primary amine)	

6.3.2 Spectroscopy

NMR Spectroscopy

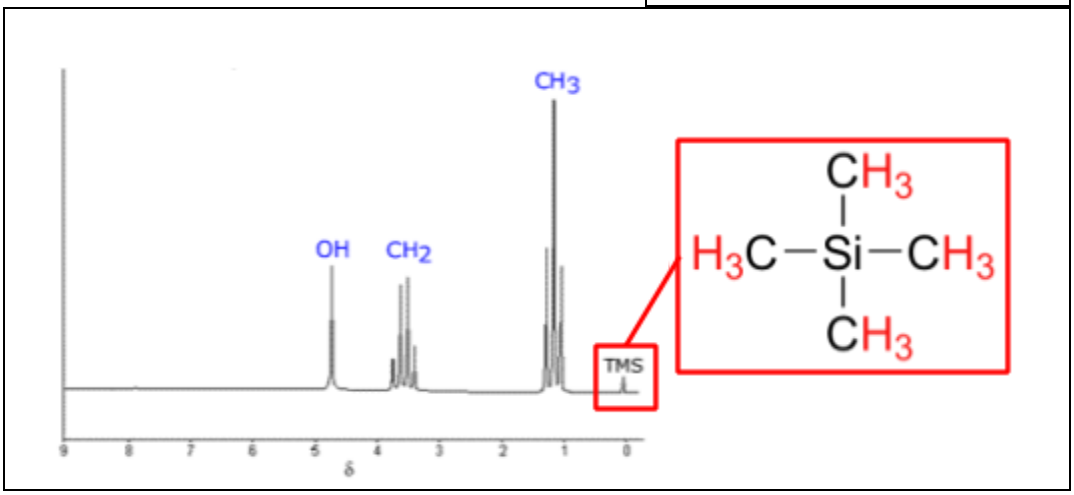
Nuclear Magnetic Resonance Spectroscopy is an **analytical technique** that allows the structure of a molecule to be determined by observing local magnetic fields around nuclei. Different chemical **environments** within a molecule are displayed as **different peaks** on a spectra print out.

NMR Spectroscopy detects nuclei that have **spin**. Hydrogen, **^1H**, and carbon-13, **^{13}C**, both have spin and can be detected by NMR. **Deuterium** is an isotope of hydrogen with a mass number of 2. It can not be detected on a proton NMR spectra. For this reason, **deuterated solvents** are often used as they do not interfere with the compound's spectra.

Carbon-12 is the most common isotope of carbon but is not detected by NMR spectroscopy. This is why carbon-13 is used, however, carbon-13 only has an abundance of roughly 1.1%, so a greater quantity of sample will be needed to obtain a well resolved spectra.

The bond environment peaks are measured against a standard molecule, **tetramethylsilane, $Si(CH_3)_4$**, known as **TMS**. This is a standard molecule as it contains four **identical** carbon and hydrogen environments. It can be easily identified as it is seen as a peak at **δ=0 ppm** on the x-axis. TMS is also **inert** so it does not interfere with the compounds being analysed.

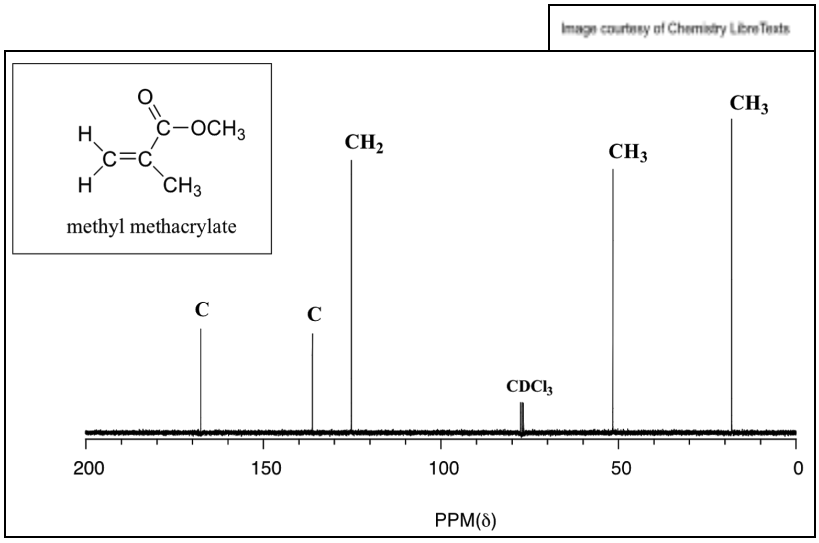
Example: A proton NMR spectra



^{13}C NMR

^{13}C NMR spectroscopy analyses the different **carbon environments** in a molecule. The different environments are shown as peaks at different δ values.

Example:



The scale on the x axis shows **chemical shift, δ**. It runs from right to left. Standard NMR chemical shift ranges will be provided for you on your data sheet in exams.

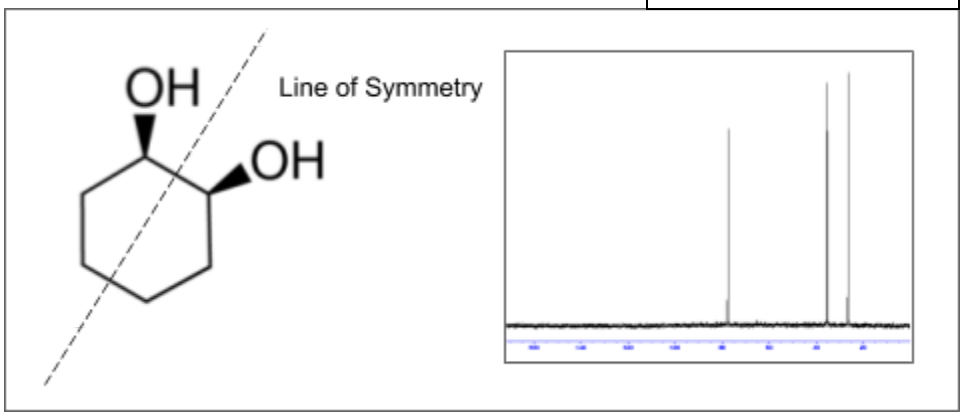
The **total magnetic field** experienced by a nucleus includes both the **external field** applied and the **local field** from neighbouring nuclei. The local field opposes the external field, so an increased electron density around a nucleus will **shield** it from the external field more and cause a **small chemical shift**. Conversely, a **reduced electron density** around a nucleus will cause it to be **deshielded** and hence have a **greater chemical shift**.

Electronegative atoms such as oxygen and nitrogen draw electron density towards themselves. This leaves adjacent carbon atoms more **deshielded.** Hence, carbon atoms neighbouring electronegative atoms have a higher shift. For this reason, carbonyl carbon atoms and those next to ester and alcohol functional groups are seen towards the left of the spectrum.

Molecules that have **symmetry** may display fewer δ peaks than the number of carbon atoms in the molecule. Therefore in these cases, it is important to look at the given **molecular formula** of the compound in order to decipher its **displayed structure**.

Example:

Images courtesy of BMRB and Sigma-Aldrich



This molecule, 1,2-cyclohexanediol, contains six carbon atoms but the NMR spectrum only has three peaks due to the symmetry of the molecule. Each peak corresponds to two identical carbon atoms.

^{1}H NMR (Proton NMR)

In ^{1}H NMR, the different **hydrogen environments** in a molecule are analysed and displayed as peaks on a spectrum. These peaks are also measured against the **TMS** standard.

The samples being analysed must be dissolved in a **non-hydrogen-containing solvent** so that the solvent doesn't produce any δ peaks on the spectrum. **CCl_4** is therefore a common solvent used along with **deuterated solvents** containing deuterium, an isotope of hydrogen. **Deuterium** has no spin so will not be detected on an NMR spectrum.

^{1}H NMR spectra are more complex than ^{13}C spectra as the **integrals** of the peaks show the **relative intensity** of each δ value. These relative intensities correspond to the number of hydrogens in that certain environment within a molecule. The integral is the area below the peak. The **ratios** of the integrals on a spectrum can be used along with the molecular mass from mass spectrometry to work out the formula of a compound.

Different types of proton environment have different **chemical shift** values in the same way as for the ^{13}C spectra. The three protons in a methyl, $-CH_3$, group are all chemically identical so one peak with a **relative intensity** of 3 will be seen.

The chemical shift scale for proton NMR is much smaller than for ^{13}C. It typically runs from **0-10 ppm**. Again, chemical shift ranges for key functional groups will be provided on your data sheet in an exam.

Splitting Patterns

The peaks of a ^{1}H NMR spectra also inform **where each environment is positioned** within the molecule. Peaks are split into a **small cluster,** indicating how many hydrogens are on the **adjacent carbon atom** within the molecule. These smaller peaks are a **splitting pattern** and follow an **'n+1' rule**, where n is the number of identical hydrogen atoms on the adjacent carbon:

- **Singlet** = 0 H on adjacent carbon
- **Doublet** = 1 H on adjacent carbon
- **Triplet** = 2 H on adjacent atom
- **Quartet** = 3 H on adjacent carbon

Example:

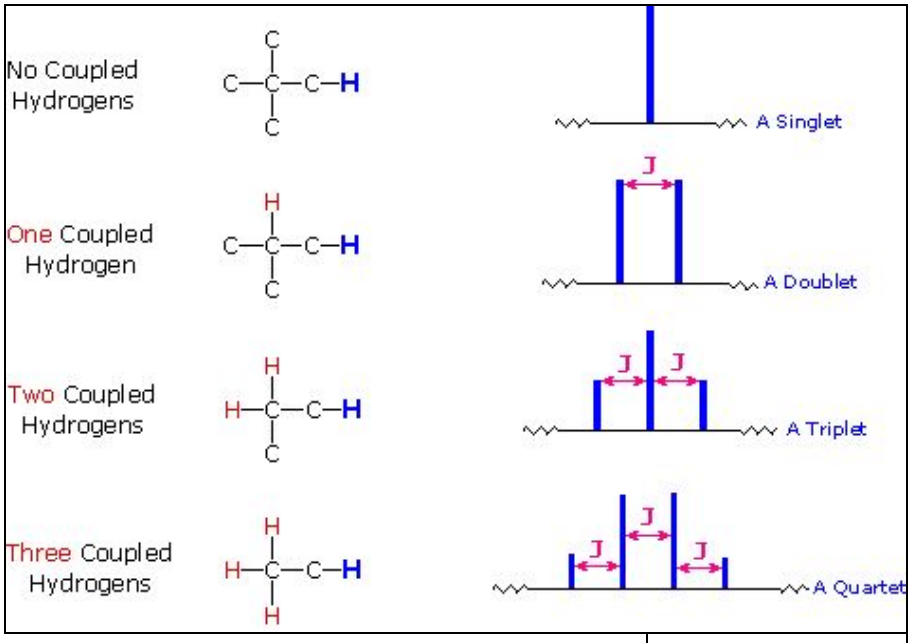


Image courtesy of MSU Chemistry

There are some common **combinations of peaks and splitting patterns** that make deciphering the structure of the molecule easier. A **triplet-quartet** splitting pattern is a common combination as it represents a **-CH_2-CH_3** fragment. The two protons on the CH_2 group split the CH_3 peak into 3 (a triplet), by the **n+1 rule**. Likewise, the three protons on the CH_3 group split the CH_2 peak into 4 (a quartet). The **relative intensities** would be 3 and 2 for the triplet and quartet respectively.

Multiple fragments can be worked out from these peaks and **pieced together** to determine the **full molecule structure**.

Hydrogen Bonding

The process of **hydrogen/deuterium exchange** can be used to identify **N-H** and **O-H** peaks in an NMR spectra. By adding **D_2O** to the sample, any protons bonded to electronegative atoms will be able to **hydrogen bond** to D_2O. This weakens the O-H or N-H bond and allows the proton to exchange with a deuterium atom. As a result, the peak will now **disappear** from the spectra since deuterium can not be detected on a ^1H spectra. Analysis of peaks can be made easier by placing the spectra with and without D_2O present next to each other and comparing peaks.

Combined Techniques

The analytical techniques covered throughout the course can be used together to predict the structure of unknown compounds. Calculations for amount of substance from module 2.1.3 can be used for **elemental analysis** alongside the analytical techniques below.

Mass Spectrometry

This is an **analytical technique** used to identify different molecules and find the overall relative molecular mass. It is covered in detail in module 4.2.4.

The ***Mr*** (relative molecular mass) of a compound **can be calculated** by looking at the m/z value of the **molecular ion peak**. This is the peak that is furthest to the right on the spectrum. Other analytical techniques can be used to determine the empirical formula, then scaled up to the Mr value from mass spectrometry to give the molecular formula.

If **fragments** are present, this can also help to deduce the structure of the compound.

High Resolution Mass Spectrometry

High resolution mass spectrometry is a much **more sensitive** form of mass spectrometry which allows the Mr of a substance to be determined to **several decimal places**. Precise atomic masses can then be used to calculate the molecular formula of the compound being tested.

Once a molecular formula has been determined, you can predict **possible structures** of the compound. Knowledge of **general formulas** and **functional groups** aids this prediction.

Infrared Spectroscopy

Infrared spectroscopy is an analytical technique that uses **infrared (IR) radiation** to determine the **functional groups** present in organic compounds. It is covered in detail in module 4.2.4.

The **characteristic curves** on the spectra allow you to list functional groups present. This can then be used alongside NMR spectroscopy and mass spectrometry to determine the full structure of the compound.

Each IR spectrum has a **fingerprint region** on the right-hand side, from 500-1500 cm^{-1}. This is unique for each species, which means it acts as a molecules' 'fingerprint', allowing the molecule to be **identified**. Once a potential structure has been hypothesised, the fingerprint region of your compound can be compared to the databook region to check you have got the correct structure.

NMR Spectroscopy

The techniques covered in the previous section on **^{1}H** and **^{13}C** spectroscopy can be used to determine the **full structure** of a compound. The shift values can be analysed to predict which **groups** are adjacent to each carbon atom. If IR spectroscopy is performed first, this can be useful to assign the peaks to specific functional groups. Mass spectrometry can be used to predict the chain length. Both of these used alongside analysis of the NMR spectra should allow you to accurately **predict the structure** of a compound.