ANDERSON SERANGOON JUNIOR COLLEGE
H3 CHEMISTRY
MASS SPECTROMETRY

CONTENT

LEARNING OUTCOMES

Students should be able to:

a) outline the basic principles of mass spectrometry, with reference to
   (i) ionisation and fragmentation
   (ii) mass/charge ratio, m/z [detailed knowledge of instrumentation is not required]

b) understand the following features and use them in the interpretation and prediction of mass spectra:
   (i) molecular ion peak
   (ii) isotopic abundances including the use of (M+1) peak caused by ^{13}C and (M+2) and (M+4) peaks for the identification of halogen compounds
   (iii) major fragment ions [fragment ions obtained from rearrangements are not included]

1. INTRODUCTION

1.1 Mass Spectrometry

Mass spectrometry is an analytical technique for measuring the mass, and therefore the molecular weight of a molecule. It enables us to determine the chemical composition of a sample and elucidate the structures of compounds based on the mass-to-charge (m/z) ratio of the charged particles.

1.2 Basic Principle

Charged particles of different mass and charge behave differently in an electric or magnetic field. A beam of positively charged particles moving across an electric field will deviate from its original path and get deflected towards the negative plate. Similar to the deflection in electric field, when a positively charged particle moves through an applied magnetic field, the particle would also experience deflective force.

Hence, for a positively charged particle of mass (*m*), velocity (*v*) and charge (*z*) passing through a magnetic field with field strength (*B*), the radius of deflection (*r*) follows the following equation:

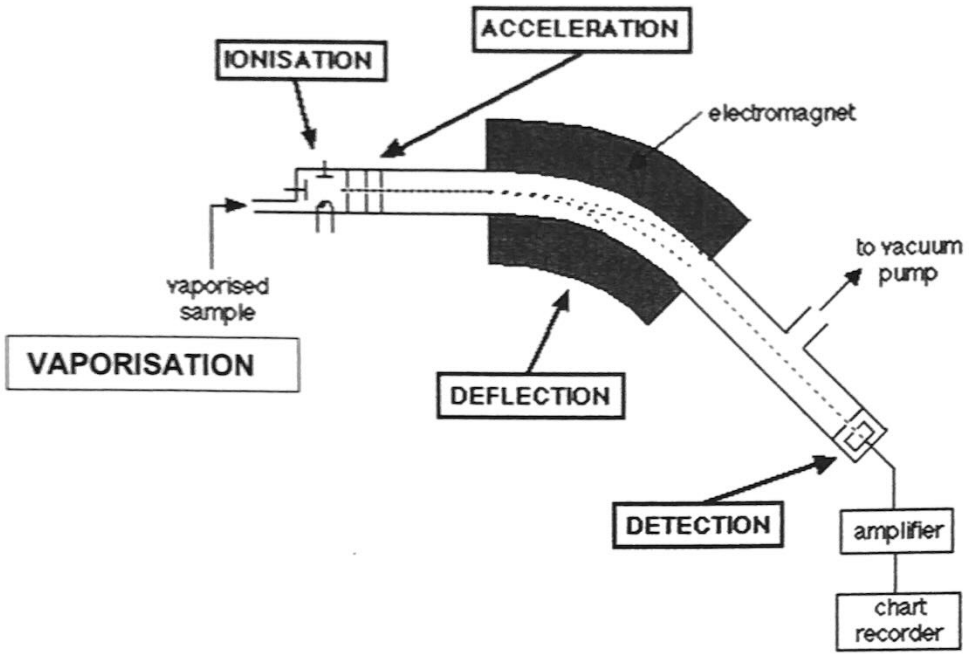
$$r = \frac{mv}{Bz}$$

For particles that have the same velocity in the same magnetic field, the radius of deflection is only dependent on the m/z ratio. Hence, we can vary the strength of the applied magnetic field to bend different particles travelling at the same velocity to the same radius of deflection. The m/z ratio of the particle can then be calculated from the velocity, magnetic field strength and radius of the path.

2. Basic Features of a Mass Spectrometer

The mass spectrometer is the instrument that performs the process of deflection of charged particles in a magnetic field. It is operated under an ultra-high vacuum to exclude the presence of air molecules which would interfere with the trajectory of the ions.

Mass spectrometry comprises five basic processes:



2.1 Vaporisation

The compound has to be converted into the gaseous form via heating before it is introduced into the ionisation chamber. The compound must not break down after vaporisation to ensure that the molecule as a whole is intact. This would enable us to determine the relative molecular mass of the compound.

2.2 Ionisation

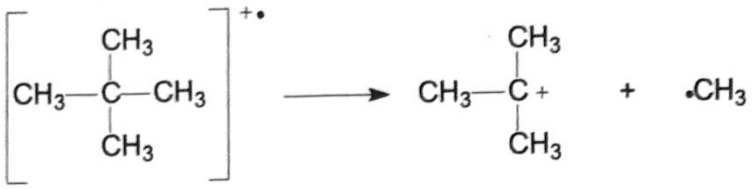
The gaseous molecules now pass through an ionisation chamber where high energy electrons from electron gun are fired at the gaseous molecules.

This will dislodge a valence electron from the molecule, producing a *cation radical*. It is a cation as the molecule has lost an electron and now has a positive charge. At the same time, it is called a radical as the species now has an odd number of electrons.

$$M + e^- \longrightarrow [M]^{+\bullet} + 2\,e^-$$

These cations usually undergo fragmentation through bond breaking to form cations and neutral radicals.

For example, the molecular ion of 2,2-dimethylpropane can undergo fragmentation to form a methyl radical and a tert-butyl carbocation.



2.3 Acceleration

The positively charged ions formed now pass through an electric field. This to accelerate all ions to approximately the same velocity such that during the deflection stage, the radius (r) of deflection is dependent on the mass (m) and charge (z) of the particle and not on the velocity (v). This relationship is represented in the following equation:

$$r = \frac{mv}{Bz}$$

2.4 Deflection

The highly energetic ions pass through the poles of an electromagnet, which causes ions of different masses and charges to deflect differently. The magnetic field strength of the electromagnet varies from low-field strength to high-field strength in order to allow these ions to be captured by the detector after they have moved through a circular pathway of a fixed radius. Hence, for a given strength of magnetic field, only ions of a specific m/z ratio pass through the slit and hit the collector plate.

2.5 Detection

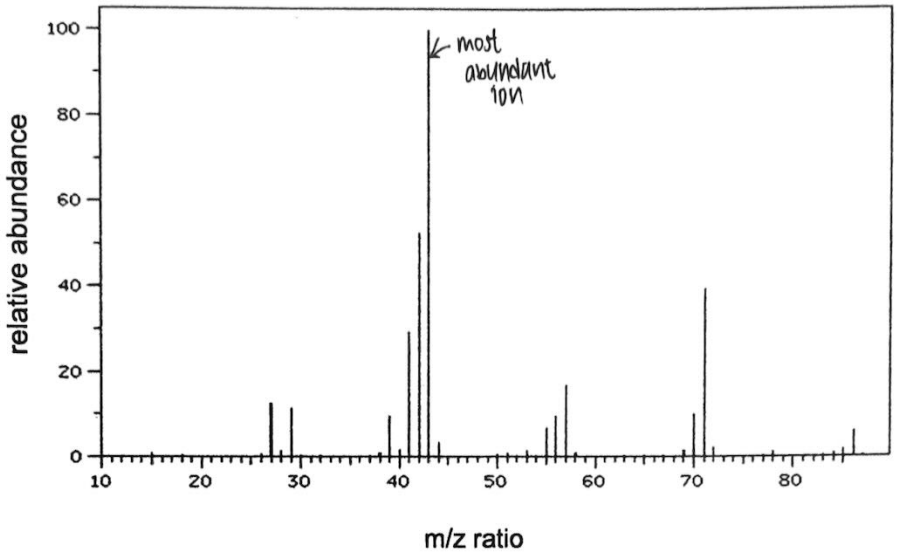
The ion beam of a particular m/z ratio is focused and hits the collector plate, causing a current to flow. This current is amplified and recorded. An output known as the mass spectrum is produced. The mass spectrum is a plot of the relative abundance (measured by the amount of current detected) against the m/z ratio.

3. MASS SPECTRUM ANALYSIS

The vertical axis, labelled as signal intensity or peak height, indicates the relative abundance of the ions. An ion of greater abundance will produce a taller peak due to its greater stability under the conditions in the spectrometer. The tallest peak is known as the base peak, and its intensity is assigned as arbitrary value of 100. All other intensities are measured and calculated relative to the base peak.

The horizontal axis shows the m/z ratio of the ion responsible for a given peak. For singly charged ions, the m/z ratio is numerically equivalent to its mass.

The mass spectrum of 2-methylpentane is given below.



3.1 Determination of Relative Atomic Mass, A_r of an Element

An analysis of the mass spectrum of an element that has isotopes allows us to calculate its relative atomic mass, A_r. This is the weighted average of the masses of the ions corresponding to the different isotopes.

For example, the mass spectrum of magnesium contains the following peaks:

m/z	relative abundance
24	100
25	12.9
26	14.4

The relative atomic mass may be calculated as follows:
A_r = [(100 x 24) + (12.9 x 25) + (14.4 x 26)] / (100 + 12.9 + 14.4) = **24.3**

3.2 Determination of Structures of Organic Compounds

The peaks shown on a mass spectrum can be classified into distinct sets that are useful in analysis:

- molecular ion peak
- peaks due to isotopes
- peaks due to fragmentation of molecular ion

When a molecule is ionised, it loses an electron and forms a singly charged molecular ion.

$$M + e^- \longrightarrow [M]^{+\bullet} + 2\,e^-$$

Usually the molecular ion peak is the one with the largest m/z ratio that corresponds to its relative molecular mass.

Peaks observed at m/z ratio larger than that of the molecular ion are due to isotopic distribution as the molecule may contain atomic isotopes. Thus, a (M+1) peak is observed if a fraction of the molecules contains one higher isotope such as ^{2}H and ^{13}C which are isoptopes of ^{1}H and ^{12}C respectively. A (M+2) peak can be attributed to two higher isotopes. If we are dealing with a halogen-containing compound, the (M+2) peak is attributed to the higher isotopes of the halogens and a (M+4) peak indicates the presence of two such higher isotopes.

Furthermore, the molecular ion can fragmented in many ways which depend on which bond in the molecule is the weakest or whether the fragment that is formed is stable enough to exist under the conditions of the spectrometer.

Hence, we can obtain the structure of the parent molecule by:

(a) determining the no. of carbon atoms in a molecule by measuring the relative heights of the molecular ion (M) peak and the (M+1) peak;

(b) identifying halogen-containing compounds by using the (M+2) and (M+4) peaks (if any);

(c) determining the molecular formula by measuring the accurate mass of a molecular ion;

(d) by identifying the fragments produced.

3.2.1 To determine the no. of C atoms in a molecule

Naturally occurring carbon is composed of 98.9% ^{12}C and 1.1% ^{13}C (along with extremely small, and variable, amounts of ^{14}C).

Based on statistical probability, the relative abundance of the M ion to the (m+1) ion can be calculated as follows:

	(M+1)	M
CH_4	Probability of $[^{13}CH_4]^+ = \frac{1.1}{100} = 0.011$ (1.11)	Probabiility of $[^{12}CH_4]^+ = \frac{98.9}{100} = 0.989$ (100)
CH_3CH_3	Probability of $[^{13}CH_3{}^{12}CH_3]^+$ $= (0.011 \times 0.989) \times 2$ $= 0.0218$ (2.23)	Probability of $[^{12}CH_3{}^{12}CH_3]^+$ $= (0.989)^2$ $= 0.978$ (100)

· M
· (M+1)
↳ lower in intensity
↳ Presence of ^{13}C

The proportion of molecules containing at least one ^{13}C atoms increases with the number of C atoms (n). This trend suggests that the ratio of the relative abundances of the M and (M+1) peaks should be 100 to 1.1 n. Hence, we can measure the relative abundances of both peaks (M and (M+1)) and solve for n to find the total number of carbons:

$$n = \frac{100}{1.1}\left(\frac{A_{M+1}}{A_M}\right)$$

where n = number of carbon atoms
A_{M+1} = the abundance of the M+1 peak
A_M = the abundance of the molecular ion, M, peak.

Exercise

Compound **A** has a molecular ion at an m/z value of 120, with a relative abundance of 23%, and a peak at m/z 121 with a relative abundance of 2%. How many carbon atoms are in a molecule of **A**?

$$n = \frac{100}{1.1}\left(\frac{2}{23}\right)$$
$$= 7.91$$
$$\approx 8$$

∴ Compound A is likely to have 8 carbon atoms per molecule.

3.2.2 To identify halogen-containing compounds

Both chlorine and bromine occur naturally as mixtures of two isotopes, with the relative abundances shown in the table.

element	isotope	relative abundance	approximate ratio
chlorine	^{35}Cl	75.8%	3:1
	^{37}Cl	24.2%	
bromine	^{79}Br	50.5%	1:1
	^{81}Br	49.5%	

(M+2) peaks

Molecules containing **one** C*l* or Br atom show M + 2 peaks due to the isotopes of these halogens.

The ratio of intensities of the M and M + 2 peaks is therefore 3 : 1 if the halogen is C*l* and 1 : 1 if the halogen is Br. The set of peaks in the specific ratio can be used to identify compounds containing one Cl or one Br atom.

	M : M+2
Cl	3 : 1
Br	1 : 1

(M+4) peaks

Molecules containing **two** C*l* or **two** Br atoms show M + 2 and M + 4 peaks.

The ratio of intensities of the M : (M + 2) : (M + 4) peaks is 9 : 6: 1 if the halogen is C*l* and 1 : 2 : 1 if the halogen is Br. The set of peaks in the specific ratio can be used to identify compounds containing two C*l* or two Br atoms

Example: CH_2Cl_2

m/z	Fragment	Intensity	Ratio
84	$[CH_2{}^{35}Cl_2]^+$	$3/4 \times 3/4 = 9/16$	9
86	$[CH_2{}^{35}Cl{}^{37}Cl]^+$	$\left(\frac{3}{4} \times \frac{1}{4}\right) \times 2 = \frac{6}{16}$	6
88	$[CH_2{}^{37}Cl_2]^+$	$\frac{1}{4} \times 1/4 = 1/16$	1

Example: CH_2Br_2

m/z	Fragment	Intensity	Ratio
172	$[CH_2{}^{79}Br_2]^+$	$1/2 \times 1/2 = 1/4$	1
174	$[CH_2{}^{79}Br{}^{81}Br]^+$	$2 \times (1/2 \times 1/2) = \frac{1}{2}$	2
176	$[CH_2{}^{81}Br{}^{81}Br]^+$	$1/2 \times 1/2$	1

Exercise

Determine the ratio of the (M), (M+2) and (M+4) peak for bromochloromethane.

m/z	Fragment	Intensity	Ratio
128	$[CH_2{}^{35}Cl{}^{79}Br]^+$	$2(3/4 \times 1/2) = 3/4$	3
130	$[CH_2{}^{37}Cl{}^{79}Br]^+$ $[CH_2{}^{35}Cl{}^{81}Br]^+$	$2(1/4 \times 1/2)$ $+2(3/4 \times 1/2) = 4/4$	4
132	$[CH_2{}^{37}Cl{}^{81}Br]^+$	$2(1/4 \times 1/2) = 1/4$	1

why ×2

Checkpoint

Compound **H** is a useful intermediate for the synthesis of drugs. Apart from C, H and O atoms, the molecule of **H** contains at least two halogen atoms, which may be chlorine or bromine or a mixture of both.

Use the mass spectrum to determine the number of atoms of each halogen contained in a molecule of **H**.

m/e value	% abundance	
75	14.7	
111	25.7	
113	8.7	
139	100.0	
141	34.7	
232	5.7 M	3
234	7.6 M+2	4
236	1.9 M+4	1

H contains 1 chlorine & 1 Bromine atom

3.2.3 To determine the molecular formula

Using **very high resolution** mass spectrometry, we can measure m/z ratios to an accuracy of 5 significant figures (1 part in 100,000). This means that it is not only possible to measure the M_r value of a compound, but also to determine its molecular formula. We can do this because the accurate relative atomic masses of individual atoms are not exact whole numbers.

name	**structure**	**molecular formula**
pentene	$CH_3CH_2CH_2CH{=}CH_2$	C_5H_{10}
aminopropanonitrile	$CH_3CH(NH_2)CN$	$C_3H_6N_2$
but-1-ene-3-one	$CH_2{=}CHCOCH_3$	C_4H_6O

By using the following accurate atomic masses, calculate their accurate M_r values.

element	**accurate relative atomic mass**
H	1.0078
C	12.000
N	14.003
O	15.995

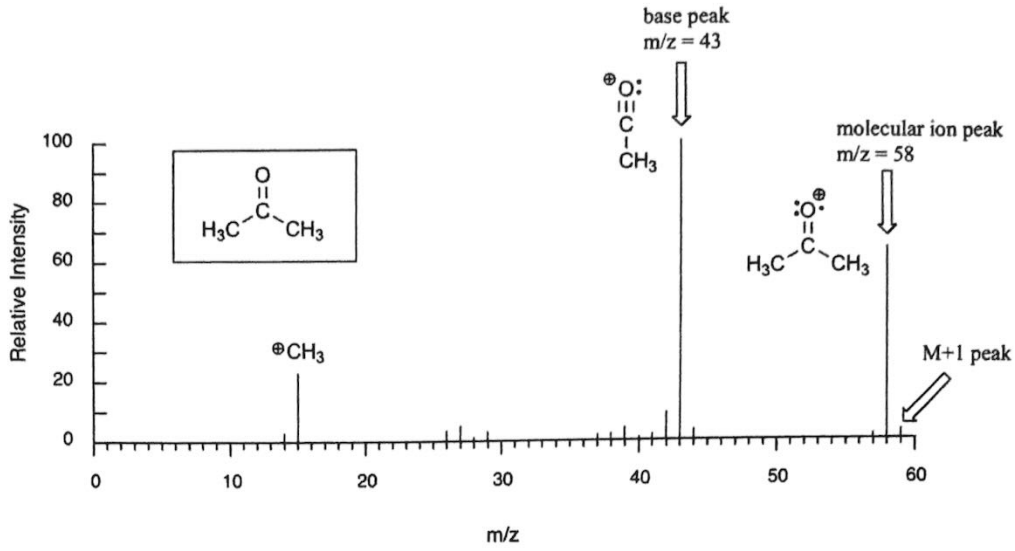
molecular formula	**M_r**
C_5H_{10}	70.078
$C_3H_6N_2$	70.052
C_4H_6O	70.045

The last two are quite close together. They differ by 7 parts in 70,000, or about 0.01%. This is well within the capabilities of a high resolution mass spectrometer.

3.2.4 To identify the fragments produced

Fragmentation of the molecular ion is valued because it provides us with the possible fragments that may be formed from a molecule. By piecing these fragments together, we can get an overall idea of the structural formula of the molecule.

Mass spectrum of propanone



In the mass spectrum of propanone, the following can be observed:

- Parent peak due to molecular ion (M^+).
- Base peak is the tallest peak due to the most abundant ion (high stability), arbitrarily assigned intensity of 100%.
- Peaks due to other molecular fragments.

Factors governing fragmentation process

(a) weak bonds tend to be broken more easily

(b) stable fragments (both the ion and radical) tend to be formed

Based on the above, there are two ways of fragmentation of the molecular ion, M^+. There could be further fragmentation of the fragment ions too. Overall, only the positively charged species will be detected.

(i) $M^{+\bullet} \longrightarrow A^+ + B^\bullet$

A^+: even-electron cation; $B^\bullet$: radical (odd number of electrons)

A^+ (even-electron cation) $\xrightarrow{\text{further fragmentation}} C^+ + D$

C^+: even-electron cation; D: neutral molecule (even number of electrons)

(ii) $M^{+\bullet} \longrightarrow E^{+\bullet} + F$

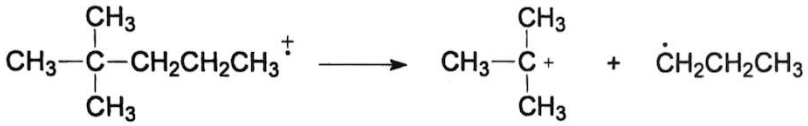
$E^{+\bullet}$: radical cation (odd number of electrons); F: neutral molecule (even number of electrons)

$E^{+\bullet}$ fragments in a similar way to $M^{+\bullet}$.

Types of bond cleavage

1. **Cleavage at branching point**

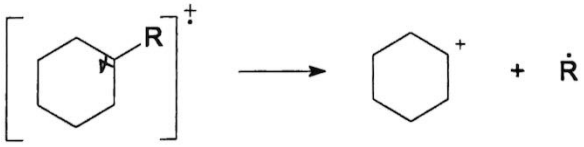
Cleavage is favoured at alkyl substituted carbon atoms; the more substituted, the more likely is cleavage (recall: stability of carbocation increases with alkyl substitution).



2. **α-cleavage**

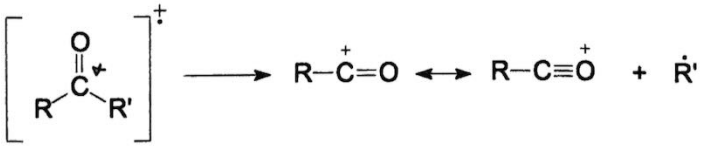
(i) α-cleavage to substituted cyclic compound

Saturated rings tend to lose alkyl side chains at the α bond and positive charge tends to stay with ring fragment.



(ii) α-cleavage to carbonyl group

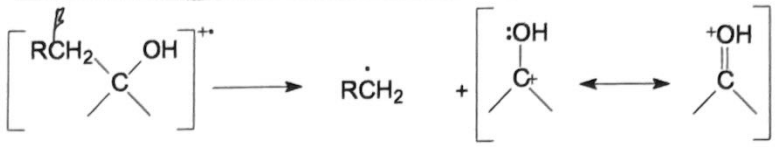
Cleavage tend to occur at the bond between the carbonyl group and the neighbouring carbon to give a neutral radical and a resonance-stabilised acyl cation.



3. β-cleavage

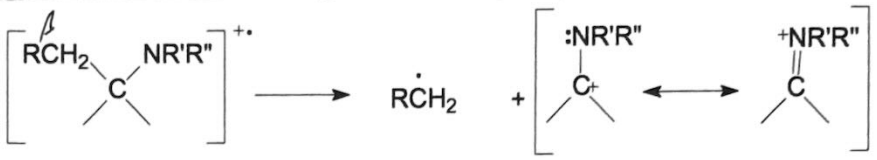
(i) β-cleavage to alcohol group

A C-C bond nearest to the hydroxyl group is broken, yielding a neutral radical and a resonance-stabilised oxygen-containing cation.



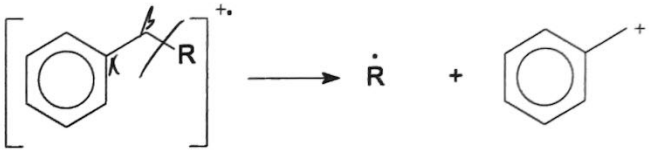
(ii) β-cleavage to amine group

A C-C bond nearest to the nitrogen atom is broken, yielding an alkyl radical and a resonance-stabilised nitrogen-containing cation.



(iii) β-cleavage to substituted aromatic ring

Cleavage is favoured at the bond β to the alkyl substituted aromatic ring, giving rise to resonance-stabilised benzyl ion.



(iv) β-cleavage to double bond

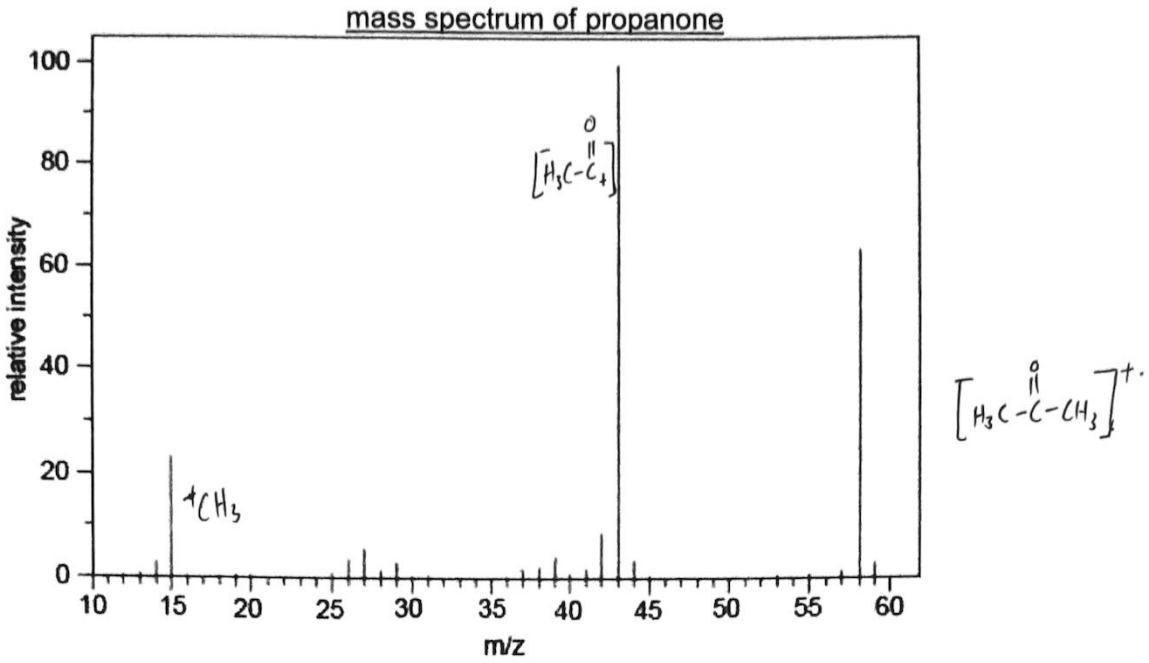
Cleavage of C–C tends to occur β to double bonds to form a resonance-stabilised carbocation.

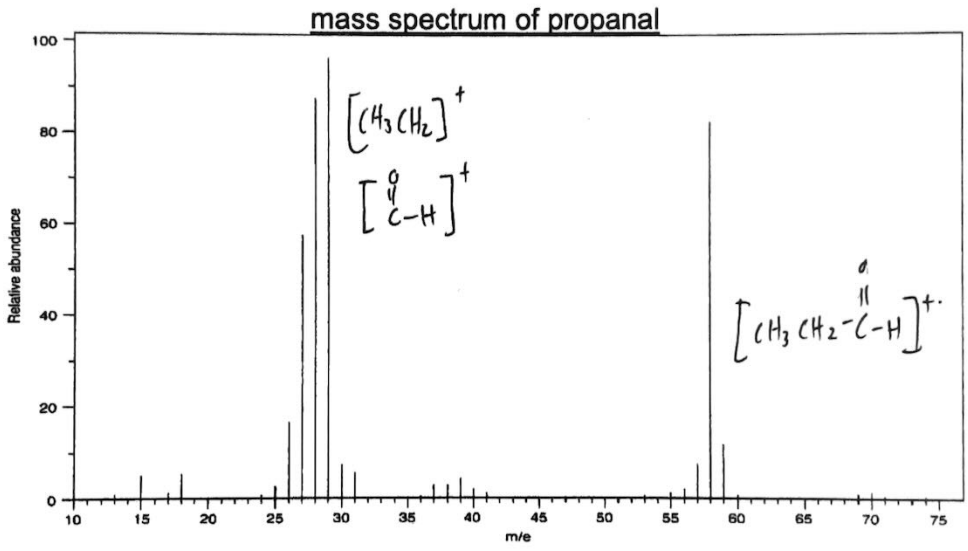
The following table lists the m/z (M_r) values of some common fragment ions.

common fragments remaining or lost	
M_r	**possible formulae**
15	CH_3
18	H_2O
26	C_2H_2
28	C_2H_4, CO, N_2
29	C_2H_5, CHO
31	CH_2OH
44	C_3H_8, CO_2, C_2H_6N, $CONH_2$
45	CO_2H
77	C_6H_5
91	$C_6H_5CH_2$

Example

Compare the spectra of propanone and propanal





Propanone

- Molecular ion ($[CH_3COCH_3]^+$) at m/z = 58
- Peak at m/z = 43

  $[CH_3COCH_3]^+ \rightarrow [COCH_3]^+ + \bullet CH_3$

  m/z = 43
- Peak at m/z = 15

  $[CH_3COCH_3]^+ \rightarrow [CH_3]^+ + \bullet COCH_3$

  m/z = 15

Propanal

- Molecular ion ($[CH_3CH_2CHO]^+$) at m/z = 58

- Peak at m/z = 57

  $[CH_3CH_2CHO]^+ \rightarrow [CH_3CH_2CO]^+ + H^\bullet$ (m/z 57) *or* $\rightarrow CH_3CH_2CO^\bullet + H^+$ (m/z = 1)

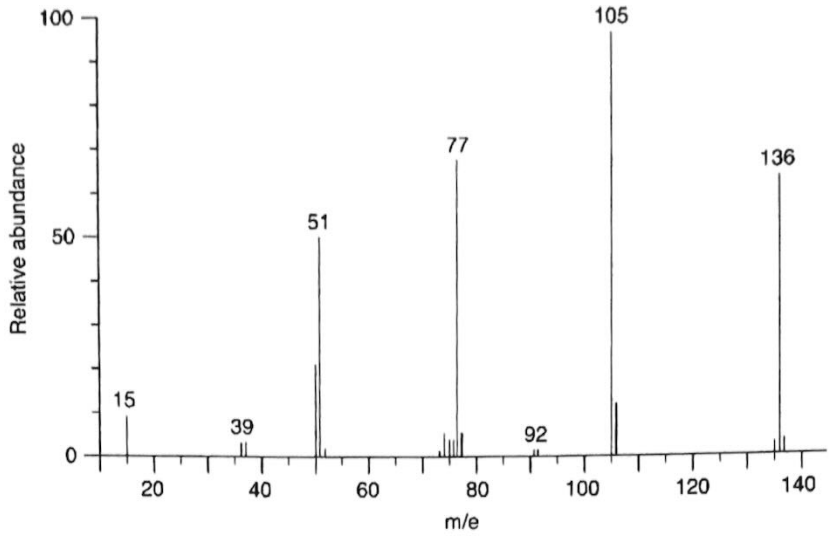
- Several peaks at m/z = 26 to m/z = 29.
  This is readily explained by the following fragmentations:

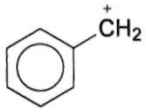
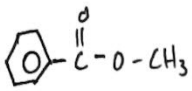
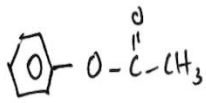
  $[CH_3CH_2CHO]^+ \rightarrow [CH_3CH_2]^+ + {}^\bullet CHO$ (m/z = 29) *or* $\rightarrow CH_3CH_2^\bullet + [CHO]^+$ (m/z = 29)

- Comparing to the spectrum of propanone, there are no peaks at m/z = 15 and m/z = 43.

Example

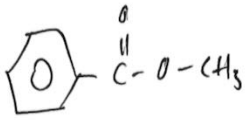
Determine the structure of an unknown compound **B** using the following spectrum of The empirical formula of compound **B** is C_4H_4O. The intensity of M:(M+1) is 11.5:1.



Information/Peak	**Deduction**
M:M+1 = 11.5:1	$n = \left(\frac{100}{1.1}\right)\left(\frac{1}{11.5}\right) = 7.9 \approx 8$
Molecular ion m/z = 136	$C_8H_8O_2$
High C : H ratio	Possible presence of 
m/z = 77	$[C_6H_5]^+$
m/z = 15	$[CH_3]^+$
Absence of m/z = 91	Absence of  Structure could be: A:  B: 
Base peak (most stable fragment) at m/z = 105	Loss of 136 – 105 = 31 $[C_8H_8O_2]^+ - CH_3O \rightarrow [C_7H_5O]^+$ 136 31 105
m/z = 77	Loss of 136 – 77 = 59 $[C_8H_8O_2]^+ - C_2H_3O_2 \rightarrow [C_6H_5]^+$ 136 59 77

m/z = 105 m/z = 77	Loss of 105 – 77 = 28 $[C_7H_5O]^+$ - CO → $[C_6H_5]^+$ 105 28 77 $[C_6H_5]^+$ + CO → $[C_6H_5CO]^+$ 77 28 105

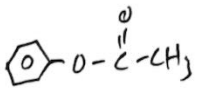
Hence compound B will take the form of structure A:



Absence of peaks:

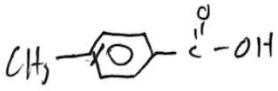
- Due to the stability of acyl cations, the presence of **phenyl ethanoate** will produce a fragment at m/z 43,

$[CH_3\text{-}CO\text{-}O\text{-}C_6H_5]^+$ - OC_6H_5 → $[CH_3\text{-}CO]^+$
m/z = 136 m/z = 43



- and **methylbenzoic acid** will produce a fragment at m/z 119.

$[CH_3\text{-}C_6H_4\text{-}COOH]^+$ - OH → $[CH_3\text{-}C_6H_4CO]^+$
m/z = 136 m/z = 119



The absence of both these peaks confirms that **B** cannot be either of these compounds.