Chapter 20 - Molecular Mass Spectrometry

Read pp. 550-570  Problems: none

MS is probably the most widely applicable of all the analytical tools available.

1. Elemental composition of samples of matter.
2. Structures of inorganic, organic and biological molecules.
3. Qualitative and quantitative composition of complex samples.
4. Structure and composition of solid surfaces.
5. Isotopic ratios of atoms in samples.
FIGURE 11-1 Components of a mass spectrometer.
Detectors for Mass Spectrometry

Electron multiplier – 20 dynodes, Gain = $10^7$
Rugged, reliable and fast response time
Detectors for Mass Spectrometry

**FIGURE 11-3** Faraday cup detector. The voltage on the ion suppressor plates is adjusted to minimize differential response as a function of mass.

Faraday cup is simple and inexpensive. Response is independent of the energy, mass and chemical nature of the ion.
Mass Analyzers - Quadrupole

Single m/z analyzer

Upper limit ~ 400 m/z (amu)

FIGURE 11-6 A quadrupole mass spectrometer.

Whether a positive ion strikes the rod depends on the rate of movement of the ion along the z-axis, its m/z ratio, and the frequency and magnitude of the ac signal.
(+ ions produced by pulsing a sample with e- or photons (~25 kHz and 0.25 ms). Ions are accelerated into the flight tube with a pulsed electric field \( \sim 10^4 \) V. Lighter elements arrive at the detector earlier, heavier elements later. Advantages – ruggedness, unlimited mass range, rapid data acquisition rate.
Mass Analyzers – Double Sector

Corrects for directional and energy distribution of ions from source. Limits KE of ions reaching magnet.

\[ m/z = (B^2r^2e)/2V \]

Usually ions are sorted by holding V and r constant, and sweeping B.
Mass Spectrum

Spectral features depend on method of ionization!

Most ideal to have the molecular ion to remain intact so $M^+$ can be determined.

$R = \frac{m}{\Delta m}$
# Ion Sources – The Starting Point

Formation of gaseous ions. Gas phase sources – sample is vaporized and then ionized. $10^3$ Da limit. Desorption sources – sample is converted directly to gaseous ions. Applicable to non-volatile and thermally unstable samples. $10^5$ Da limit.

## Table 20-1 Ion Sources for Molecular Mass Spectrometry

<table>
<thead>
<tr>
<th>Basic Type</th>
<th>Name and Acronym</th>
<th>Ionizing Agent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas phase</td>
<td>Electron impact (EI)</td>
<td>Energetic electrons</td>
</tr>
<tr>
<td></td>
<td>Chemical ionization (CI)</td>
<td>Reagent gaseous ions</td>
</tr>
<tr>
<td></td>
<td>Field ionization (FI)</td>
<td>High-potential electrode</td>
</tr>
<tr>
<td></td>
<td>Field desorption (FD)</td>
<td>High-potential electrode</td>
</tr>
<tr>
<td>Desorption</td>
<td>Electrospray ionization (ESI)</td>
<td>High electrical field</td>
</tr>
<tr>
<td></td>
<td>Matrix-assisted desorption-ionization (MALDI)</td>
<td>Laser beam</td>
</tr>
<tr>
<td></td>
<td>Plasma desorption (PD)</td>
<td>Fission fragments from $^{252}$Cf</td>
</tr>
<tr>
<td></td>
<td>Fast atom bombardment (FAB)</td>
<td>Energetic atomic beam</td>
</tr>
<tr>
<td></td>
<td>Secondary-ion mass spectrometry (SIMS)</td>
<td>Energetic beam of ions</td>
</tr>
<tr>
<td></td>
<td>Thermospray ionization (TS)</td>
<td>High temperature</td>
</tr>
</tbody>
</table>
**Electron Impact Ionization - Hard**

\[ M + e^- \rightarrow M^{+} + 2e^- \]

KE = eVN = $6 \times 10^3$ kJ/mol (70 V)  200-600 kJ/mol bond energies

**Energetic electron beam causes molecules to lose an electron (become ionized) due to electrostatic repulsion.**

Interaction with the electron beam ionizes the molecule but it also leaves the molecule in a highly excited vibrational and rotational state. Relaxation occurs by extensive fragmentation giving a large number of positive ions of various masses that are less than the mass of the molecular ion.

Complex mass spectra are useful for compound identification.
Typical Electron Impact Mass Spectra

**FIGURE 20-4** Electron-impact mass spectra of (a) methylene chloride and (b) 1-pentanol.
# Isotopic Abundances

<table>
<thead>
<tr>
<th><strong>Element</strong></th>
<th><strong>Most Abundant Isotope</strong></th>
<th><strong>Abundance of Other Isotopes Relative to 100 Parts of the Most Abundant</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>$^1$H</td>
<td>$^2$H 0.015</td>
</tr>
<tr>
<td>Carbon</td>
<td>$^{12}$C</td>
<td>$^{13}$C 1.08</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>$^{14}$N</td>
<td>$^{15}$N 0.37</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$^{16}$O</td>
<td>$^{17}$O 0.04</td>
</tr>
<tr>
<td>Sulfur</td>
<td>$^{32}$S</td>
<td>$^{33}$S 0.80</td>
</tr>
<tr>
<td>Chlorine</td>
<td>$^{35}$Cl</td>
<td>$^{37}$Cl 32.5</td>
</tr>
<tr>
<td>Bromine</td>
<td>$^{79}$Br</td>
<td>$^{81}$Br 98.0</td>
</tr>
<tr>
<td>Silicon</td>
<td>$^{28}$Si</td>
<td>$^{29}$Si 5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{30}$Si 3.4</td>
</tr>
</tbody>
</table>

*a Fluorine ($^{19}$F), phosphorus ($^{31}$P), sodium ($^{23}$Na), and iodine ($^{127}$I) have no additional naturally occurring isotopes.

*b The numerical entries indicate the average number of isotopic atoms present for each 100 atoms of the most abundant isotope; thus, for every 100 $^{13}$C atoms there will be an average of 1.08 $^{12}$C atoms.
Chemical Ionization - Soft

\[ \text{CH}_4 + e^- \rightarrow \text{CH}_4^+ + 2e^- \]

\[ \text{CH}_4^+ + \text{CH}_4 \rightarrow \text{CH}_5^+ + \text{CH}_3 \]

\[ \text{CH}_5^+ + \text{MH} \rightarrow \text{MH}_2^+ + \text{CH}_4 \]

Spectra contain mainly the molecular ion peak (M+1) – most abundant!! There is no extensive fragmentation.
MALDI Ionization

Desorption and ionization in gas phase.

Atom transfer reactions happen in the matrix to give multiply charged.

Low background and absence of fragmentation. Multiply charged ions are present as well as peaks for dimer and trimer species.
MALDI Data

Figure 13.12 MALDI-TOF mass spectrum of a mixture of three proteins.
Electrospray Ionization

**FIGURE 20-9** Apparatus for electrospray ionization. (From J. B. Fenn et al., *Science, 1989, 65*, 246. Reprinted with permission.)
Electrospray Ionization MS Data

Dilute acetic or formic acid buffers used. Good for polar molecules. Multiply charged!!!

**FIGURE 20-10** Typical electrospray mass spectra of proteins and peptides. The numbers above the peaks represent the molecular charge associated with each peak. (From R. D. Smith et al., *Anal. Chem.*, 1990, 62, 882. Copyright 1990 American Chemical Society.)
Additional Info on ESI

John Fenn, Monsanto and Virginia Commonwealth University (shared Nobel Prize 2002)
Atmospheric Pressure Ionization

Does not produce multiply charged analytes

\[ S-H \xrightarrow{CD} [S-H]^+ \xrightarrow{A} [A-H]^+ \]
Desorption Electrospray Ionization

Mid-2000s Graham Cooks (Purdue)

DESI is a combination of electrospray (ESI) and desorption (DI) ionization methods. Ionization takes place by directing an electrically charged mist to the sample surface that is a few millimeters away. The electrospray mist is pneumatically directed at the sample where subsequent splashed droplets carry desorbed, ionized analytes. After ionization, the ions travel through air into the atmospheric pressure interface which is connected to the mass spectrometer.