

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.

Components of a Mass Spectrometer

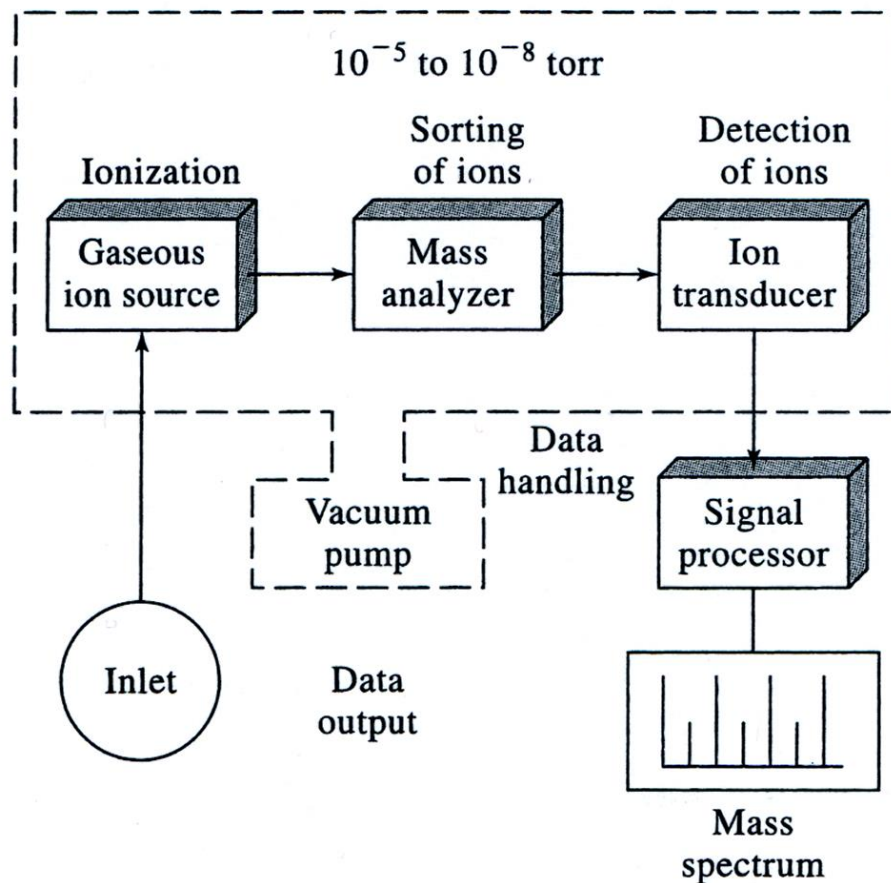


FIGURE 11-1 Components of a mass spectrometer.

Detectors for Mass Spectrometry

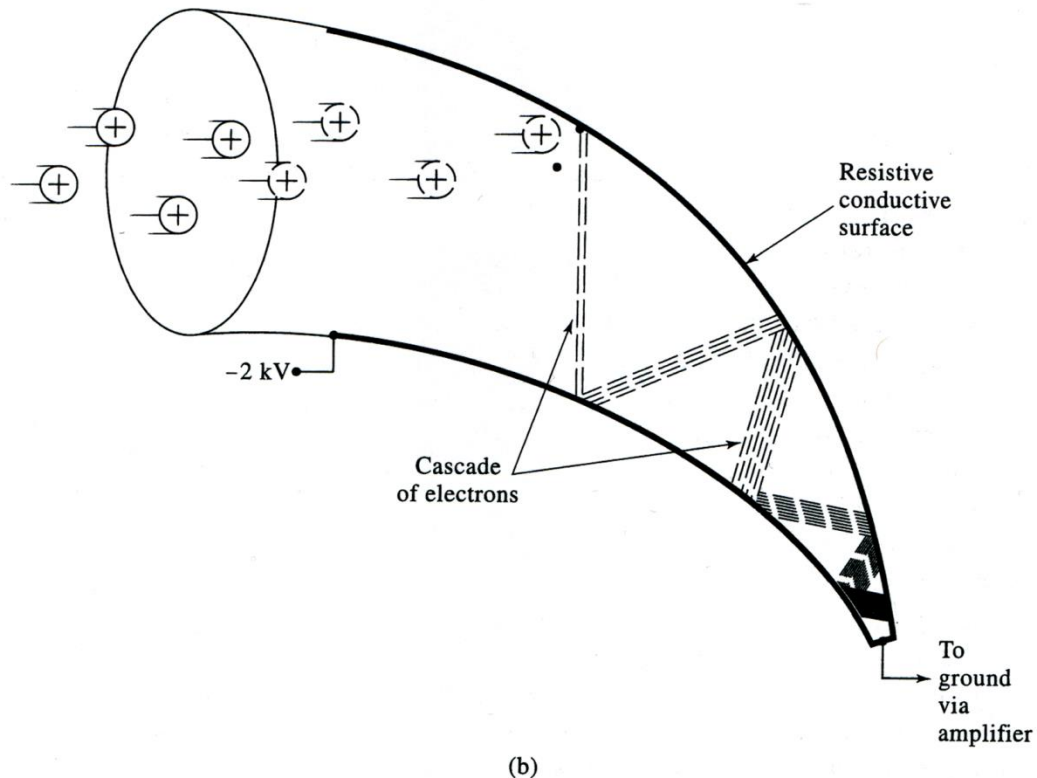


FIGURE 11-2 (a) Discrete-dynode electron multiplier. Dynodes are kept at successively higher voltages via a multistage voltage divider. (b) Continuous-dynode electron multiplier. (Adapted from J. T. Watson, *Introduction to Mass Spectrometry*, 3rd ed., pp. 334–35, New York: Raven Press, 1997. With permission.)

Electron multiplier – 20 dynodes, Gain = 10^7
Rugged, reliable and fast response time

Detectors for Mass Spectrometry

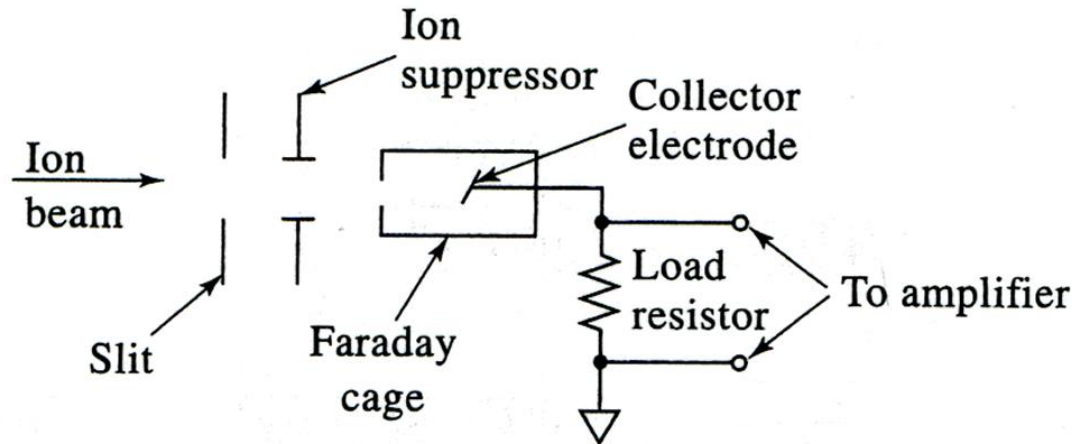


FIGURE 11-3 Faraday cup detector. The voltage on the ion suppressor plates is adjusted to minimize differential response as a function of mass.

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 $\sim 400 m/z$ (amu)

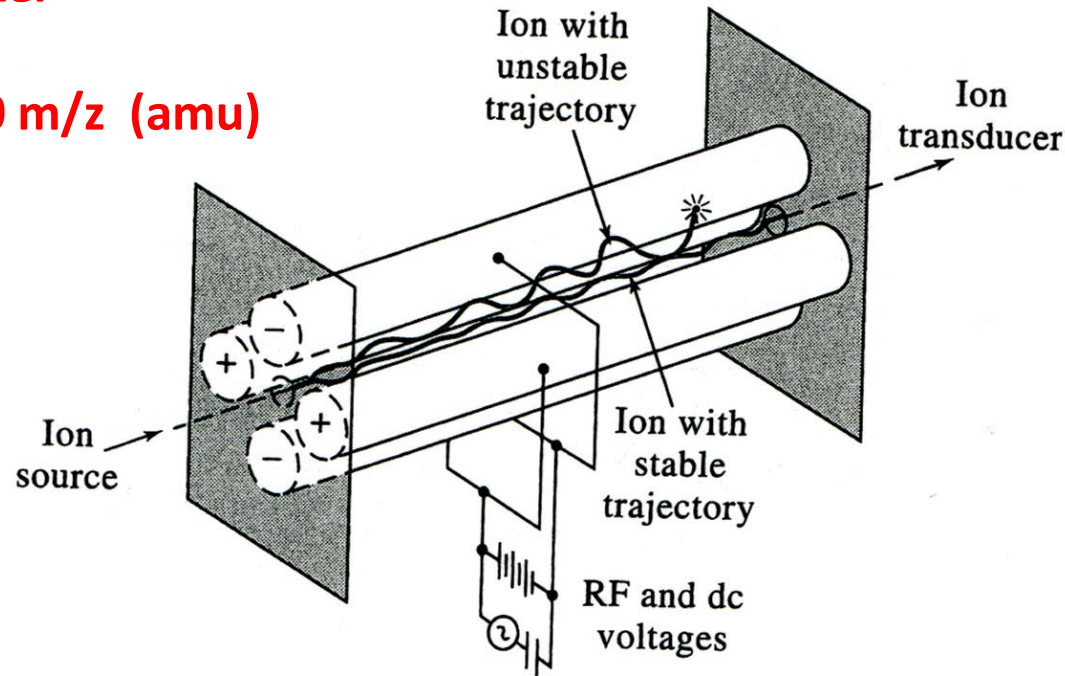


FIGURE 11-6 A quadrupole mass spectrometer.

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.

Mass Analyzers – Time-of-Flight

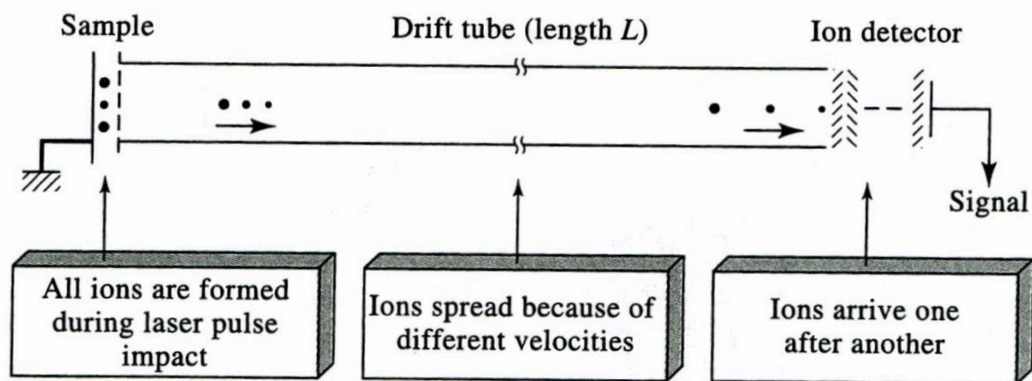


FIGURE 11-10 Principle of a TOF mass spectrometer. A spatially tightly bunched group of ions produced by a laser probe is accelerated into the drift tube where separation occurs. (From A. H. Verbueken, F. J. Bruynseels, R. Van Grieken, and F. Adams, in *Inorganic Mass Spectrometry*, p. 186, F. Adams, R. Gijbels, and R. Van Grieken, eds., New York: Wiley, 1988. With permission.)

$$zeV = KE = \frac{1}{2}(mv^2)$$

$$t_f = L/v = L (m/2zeV)^{1/2}$$

(+) 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

Double focusing improves resolution!

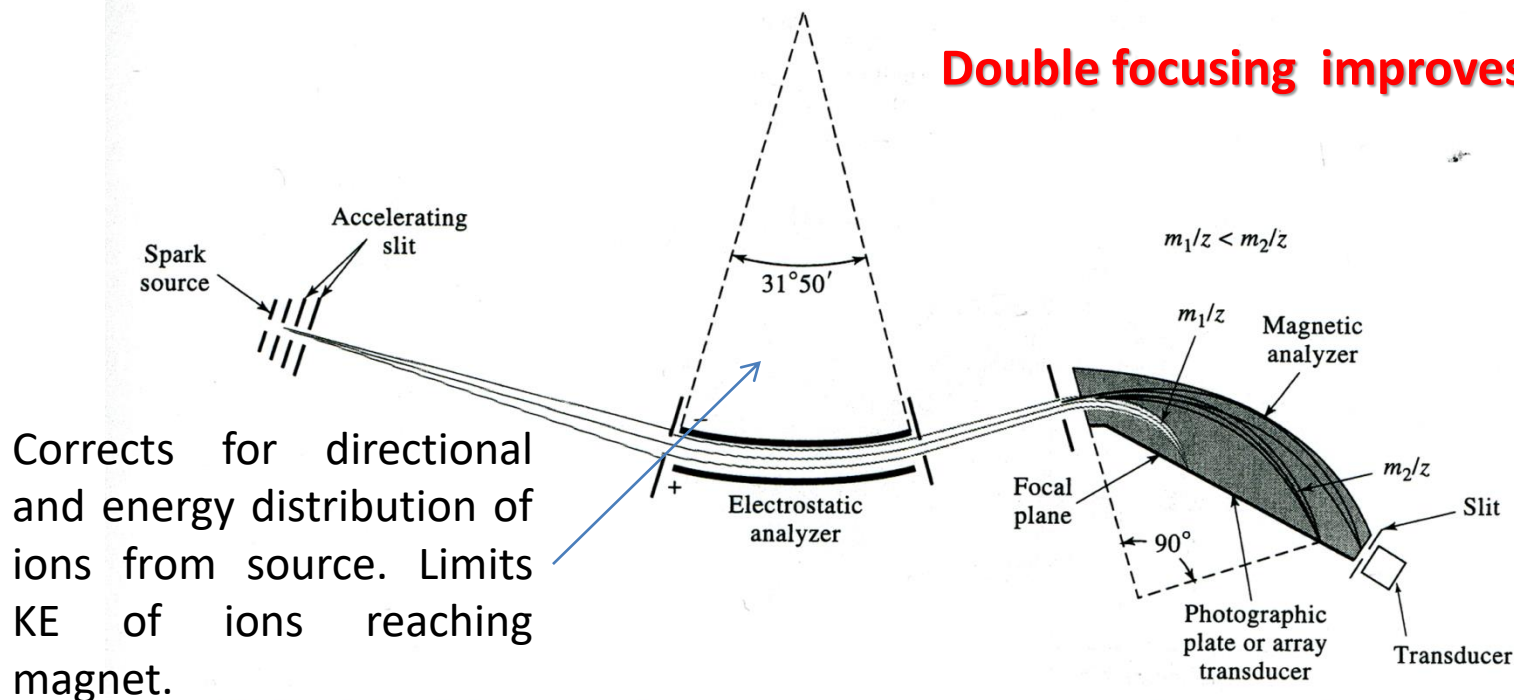
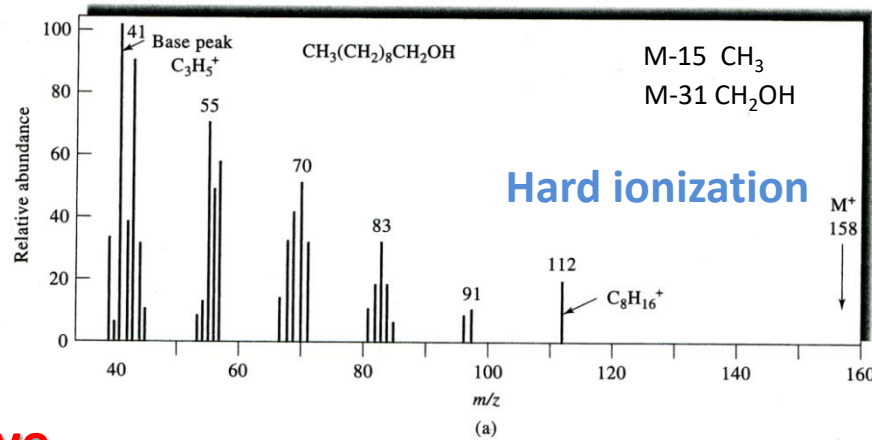


FIGURE 11-11 Mattauch-Herzog-type double-focusing mass spectrometer. Resolution $>10^5$ has been achieved with instruments based on this design.

$$m/z = (B^2 r^2 e) / 2V$$

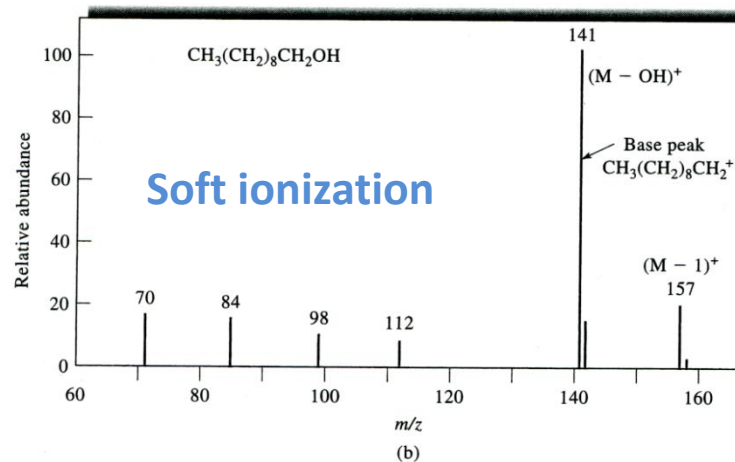
Usually ions are sorted by holding V and r constant, and sweeping B .

Mass Spectrum



Spectral features depend on method of ionization!

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



$$R = m/\Delta m$$

FIGURE 20-2 Mass spectrum of 1-decanol from (a) a hard ionization source (electron impact) and (b) a soft ionization source (chemical ionization).

Ion Sources – The Starting Point

TABLE 20-1 Ion Sources for Molecular Mass Spectrometry

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

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.

Electron Impact Ionization - Hard

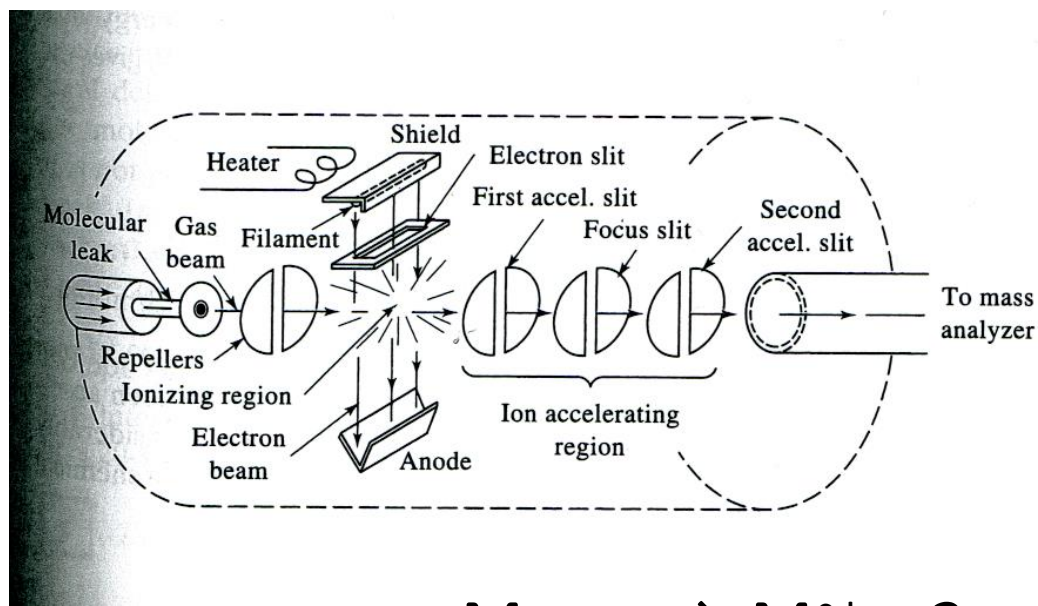


FIGURE 20-3 An electron-impact ion source. (Adapted from R. M. Silverstein and F. X. Webster, *Spectrometric Identification of Organic Compounds*, 6th ed., p. 4, New York: Wiley, 1998. Reprinted with permission of John Wiley & Sons, Inc.)



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

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

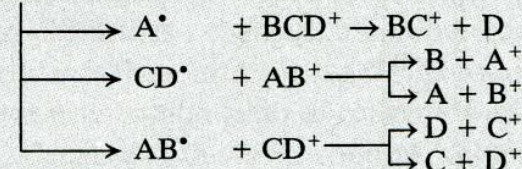
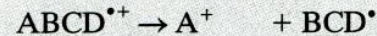
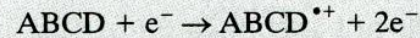
Electron Impact Spectra

Complex mass spectra are useful for compound identification.

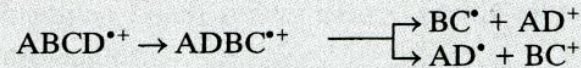
TABLE 20-2 Some Typical Reactions in an Electron-Impact Source

Molecular ion formation

Fragmentation



Rearrangement followed by fragmentation

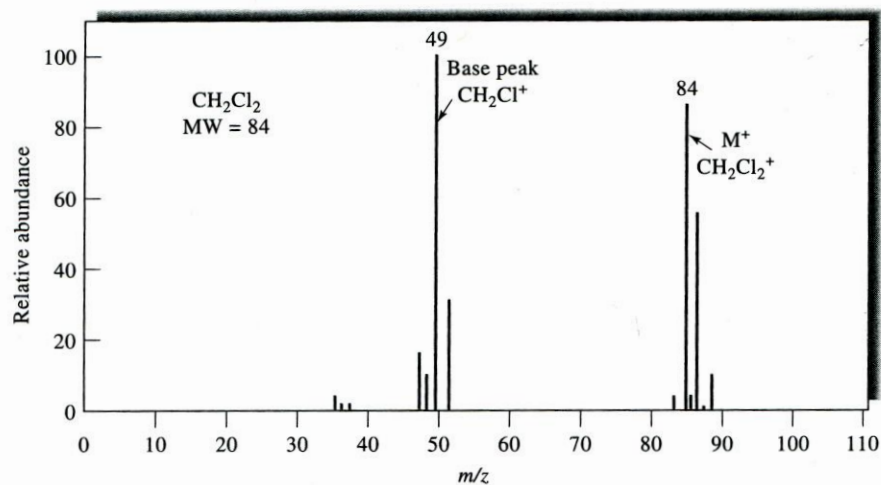


Collision followed by fragmentation

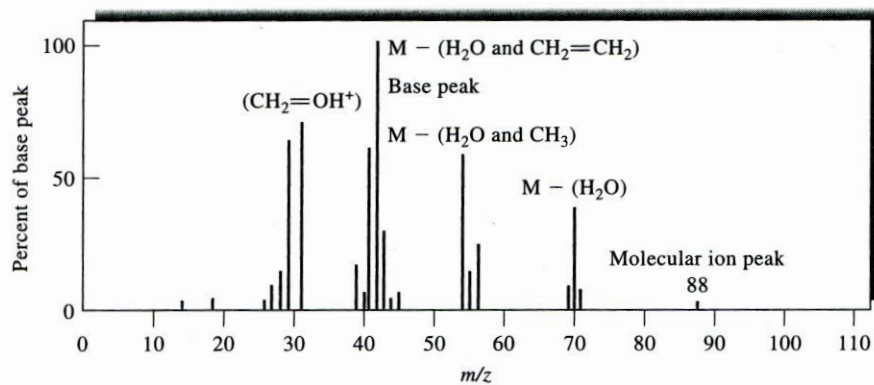


Interaction with the electron beam ionizes the molecule but it also leaves the molecule in a highly excited vibrational and rotational state. Relaxation occurs by extensive fragmentation giving a large number of positive ions of various masses that are less than the mass of the molecular ion.

Typical Electron Impact Mass Spectra



(a)



(b)

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

Isotopic Abundances

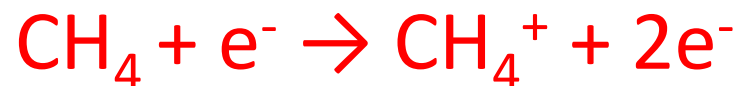
TABLE 20-3 Natural Abundance of Isotopes of Some Common Elements

Element ^a	Most Abundant Isotope	Abundance of Other Isotopes Relative to 100 Parts of the Most Abundant ^b
Hydrogen	¹ H	² H 0.015
Carbon	¹² C	¹³ C 1.08
Nitrogen	¹⁴ N	¹⁵ N 0.37
Oxygen	¹⁶ O	¹⁷ O 0.04 ¹⁸ O 0.20
Sulfur	³² S	³³ S 0.80 ³⁴ S 4.40
Chlorine	³⁵ Cl	³⁷ Cl 32.5
Bromine	⁷⁹ Br	⁸¹ Br 98.0
Silicon	²⁸ Si	²⁹ Si 5.1 ³⁰ Si 3.4

^aFluorine (¹⁹F), phosphorus (³¹P), sodium (²³Na), and iodine (¹²⁷I) have no additional naturally occurring isotopes.

^bThe numerical entries indicate the average number of isotopic atoms present for each 100 atoms of the most abundant isotope; thus, for every 100 ¹²C atoms there will be an average of 1.08 ¹³C atoms.

Chemical Ionization - Soft



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

MALDI Ionization

Desorption and ionization in gas phase.

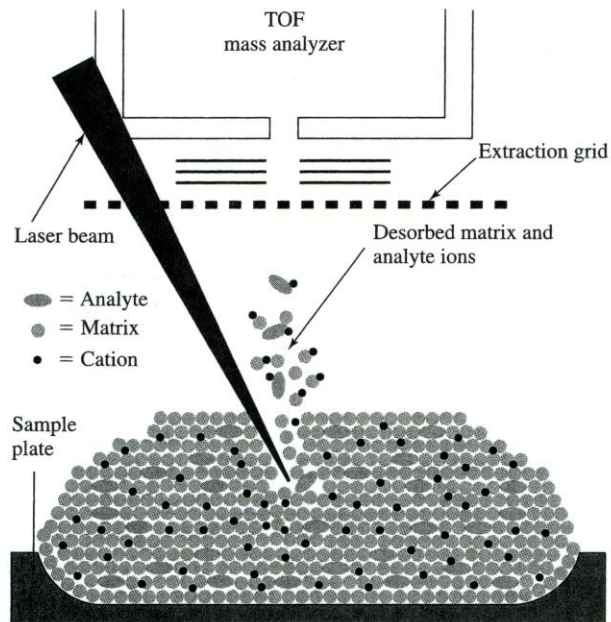
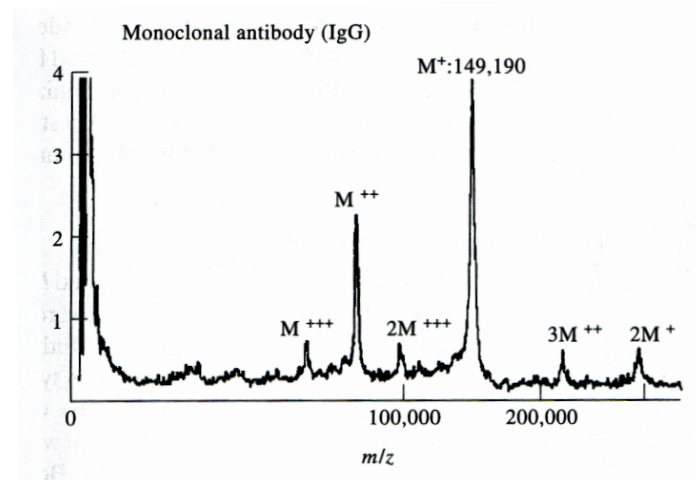


FIGURE 20-7 Diagram of the MALDI process. The analyte is uniformly dispersed in a matrix and placed on a metal sample plate. A pulsed laser beam strikes the sample causing desorption of a plume of matrix, analyte, and other ions. The analyte can be protonated, be deprotonated, or form adducts before entering the TOF analyzer.

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



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

N_2 Laser (337 nm)

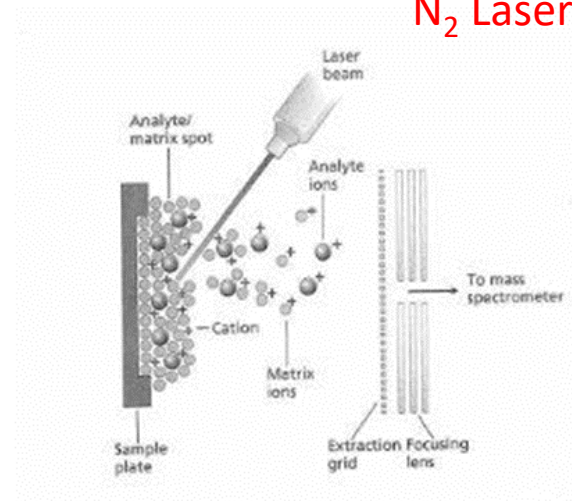


Figure 13.11 MALDI ionization.

MALDI Data

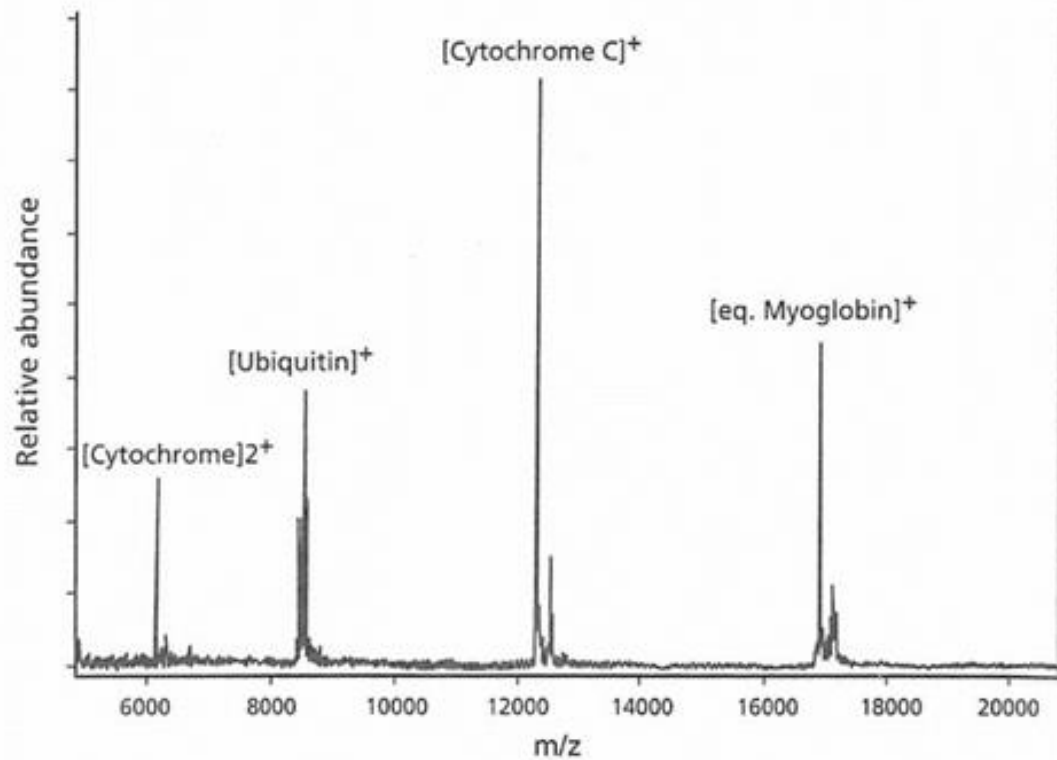


Figure 13.12 MALDI-TOF mass spectrum of a mixture of three proteins.

Electrospray Ionization

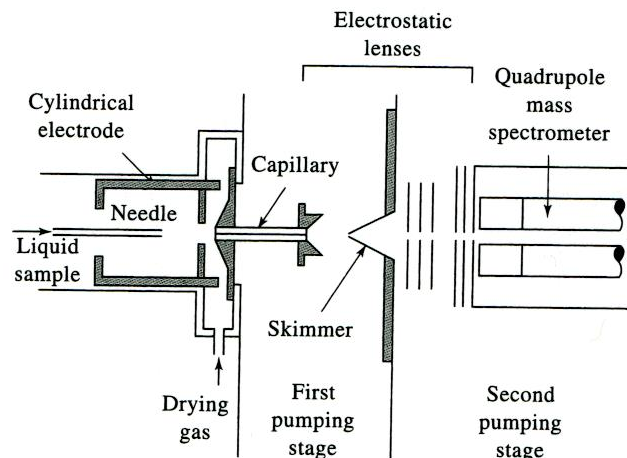
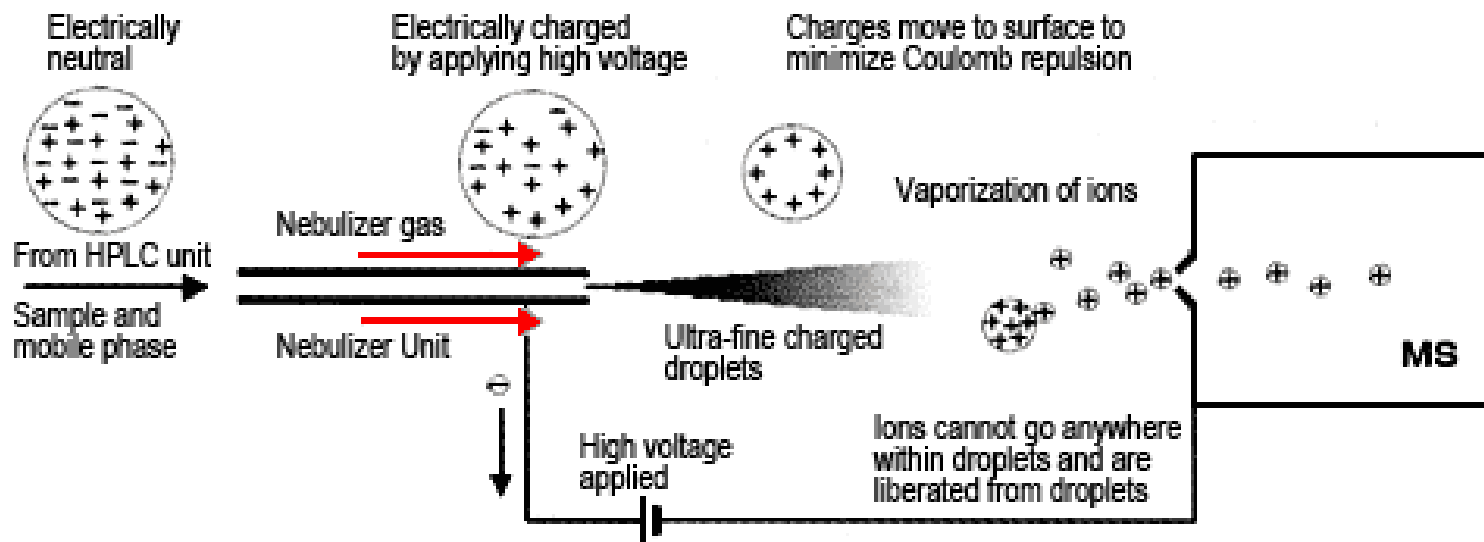


FIGURE 20-9 Apparatus for electrospray ionization. (From J. B. Fenn et al., *Science*, **1989**, 65, 246. Reprinted with permission.)



Electrospray Ionization MS Data

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

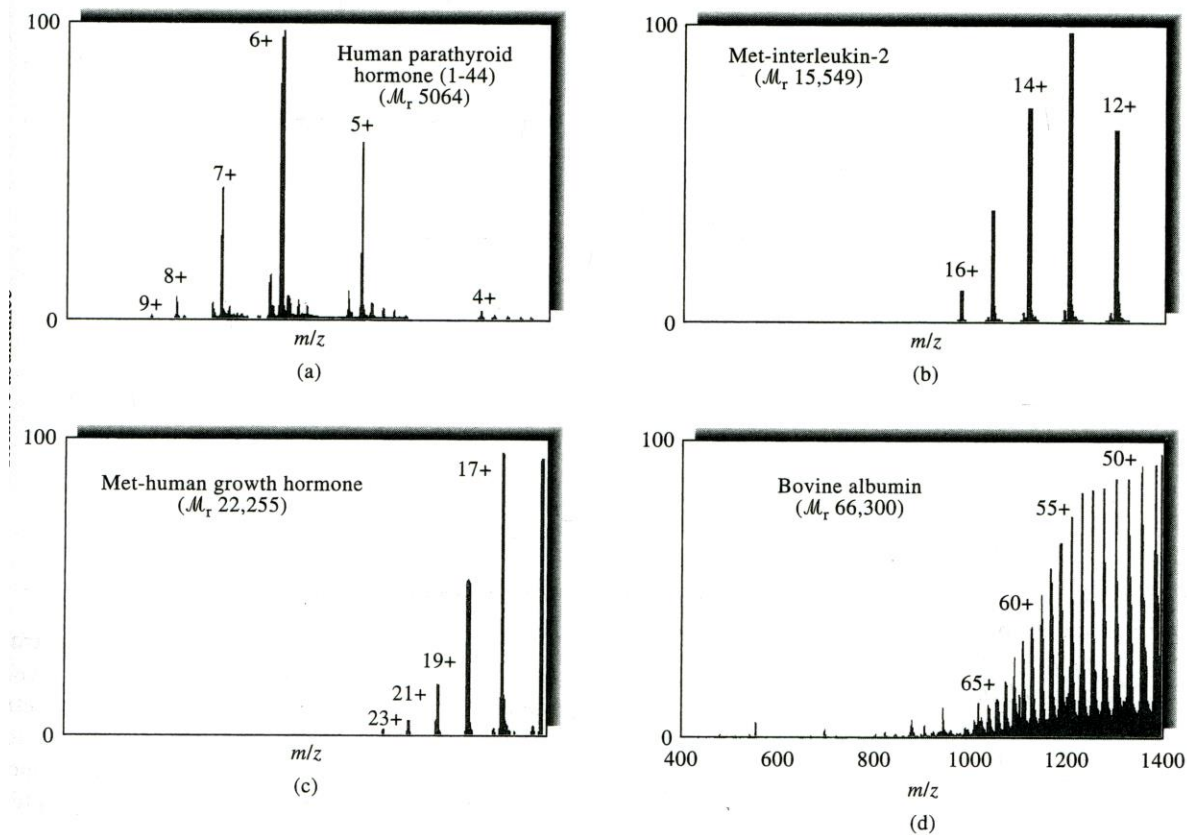


FIGURE 20-10 Typical electrospray mass spectra of proteins and peptides. The numbers above the peaks represent the molecular charge associated with each peak. (From R. D. Smith et al., *Anal. Chem.*, **1990**, 62, 882. Copyright 1990 American Chemical Society.)

Additional Info on ESI

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

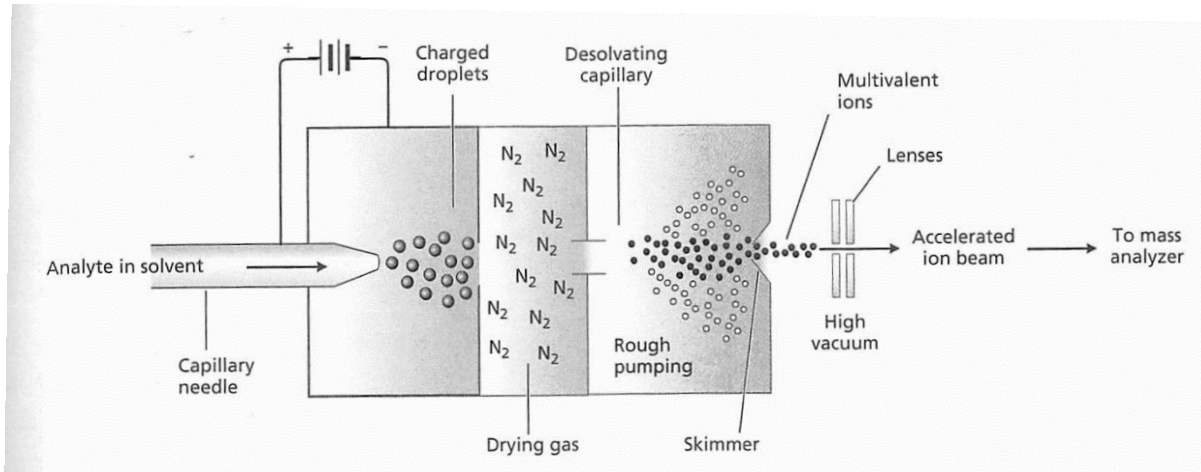


Figure 13.8 Schematic of an ESI system.

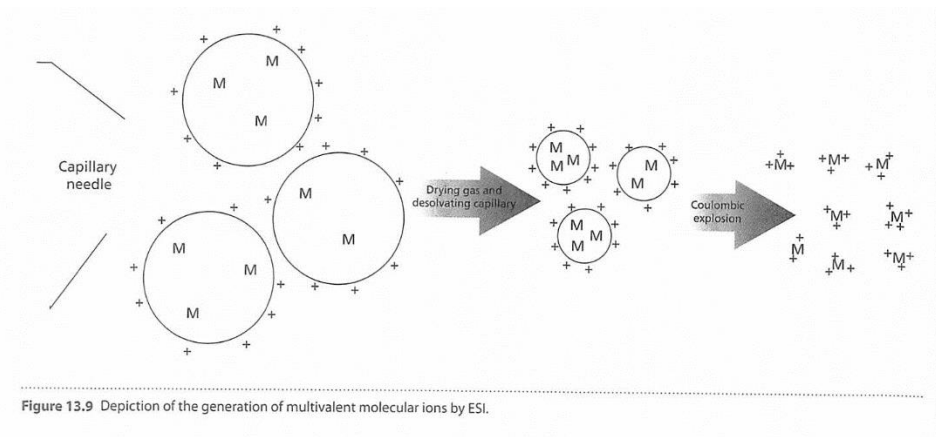


Figure 13.9 Depiction of the generation of multivalent molecular ions by ESI.

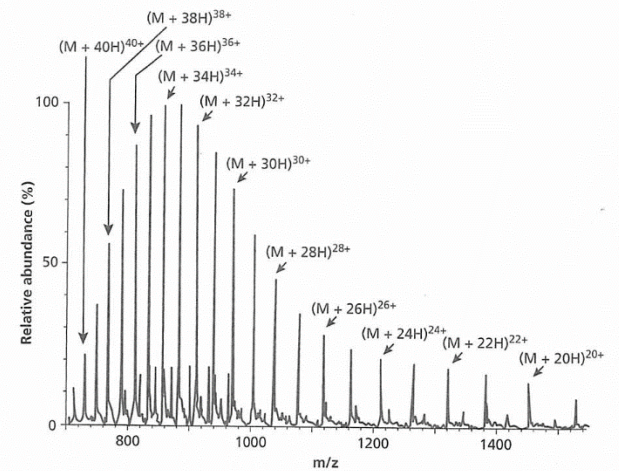
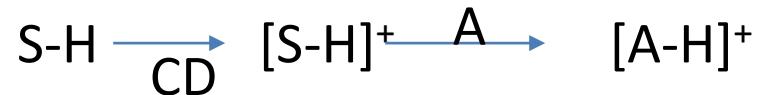
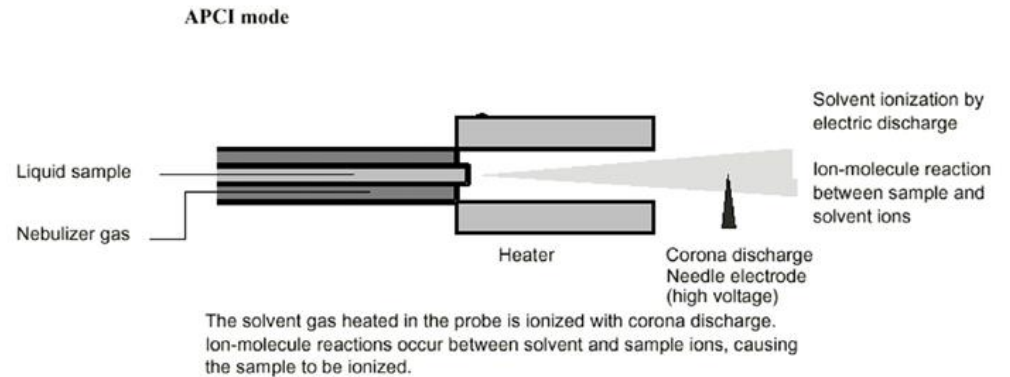
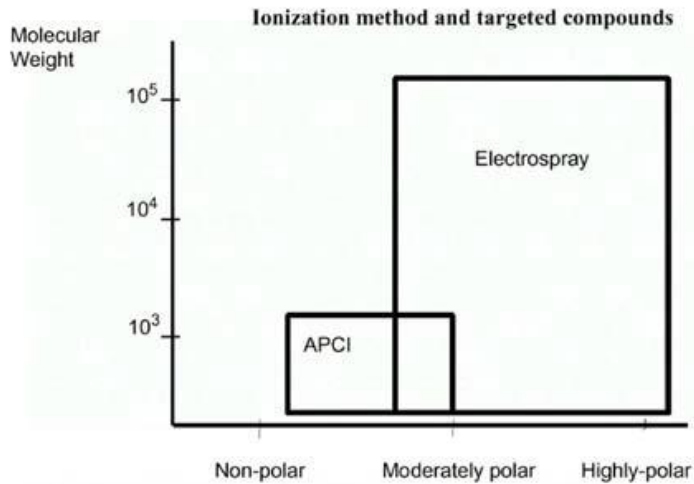
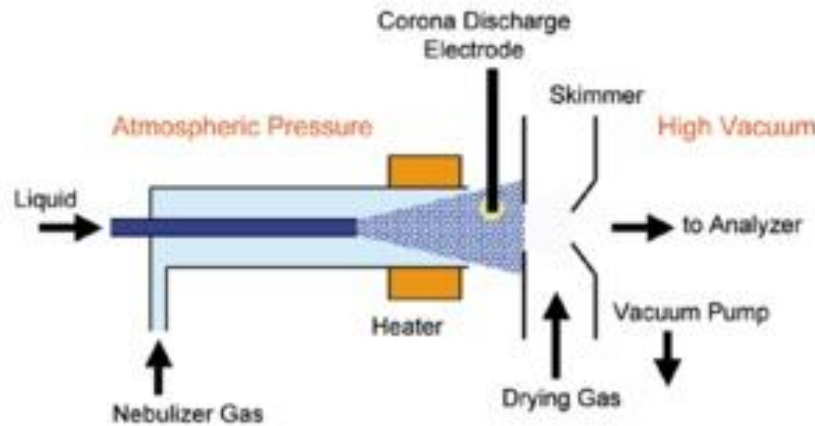


Figure 13.10 ESI-MS of the enzyme carbonic anhydrase II, 29 kDa.

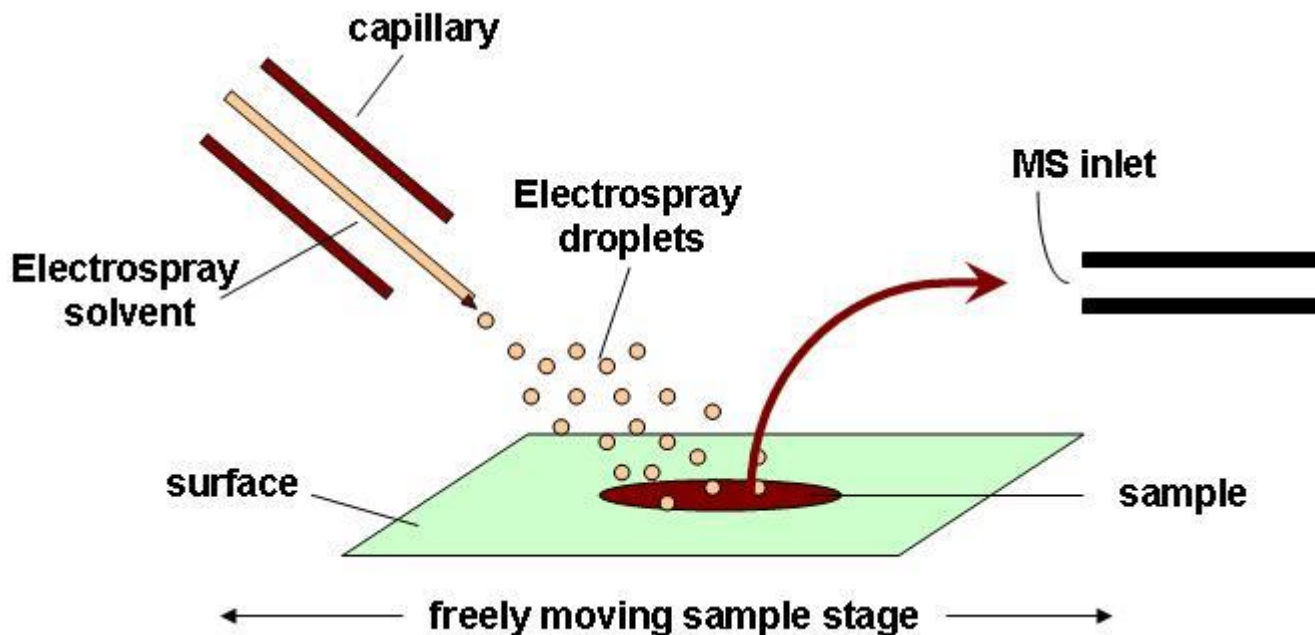
Atmospheric Pressure Ionization

Does not produce multiply charged analytes



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.^[2] The electro spray 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.