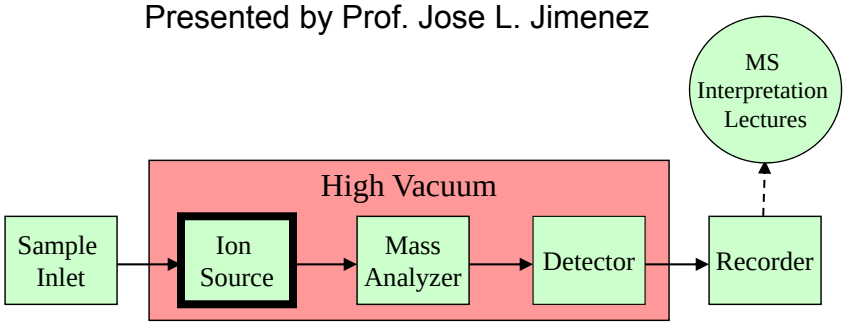
Ionization Techniques – Part IV

CU- Boulder

CHEM 5181

Mass Spectrometry & Chromatography

Presented by Prof. Jose L. Jimenez



Adapted from slides from Dr. Joel Kimmel, Fall 2007

Fast Atom Bombardment (FAB) and Secondary Ion Mass Spectrometry (SIMS)

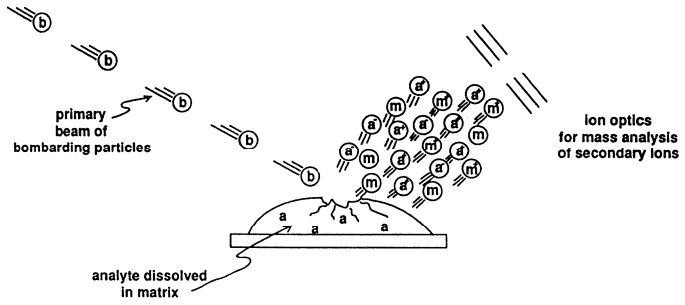


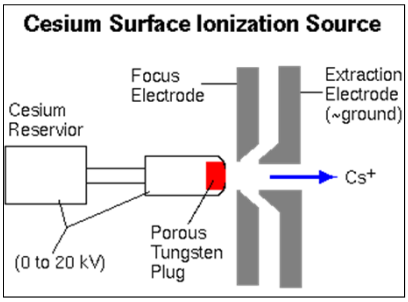
FIG. 9.1. Bombardment of a sample (dissolved in a liquid matrix) by a primary beam of atoms or ions to produce secondary ions that are characteristic of the analyte (*a*, analyte; *b*, bombarding particle; *m*, matrix).

From Watson

Desorption techniques.

Analyze the ions emitted when a surface is irradiated with an energetic beam of **neutrals** (FAB) or **ions** (SIMS).

Producing Primary Beam: SIMS vs. FAB



From de Hoffmann

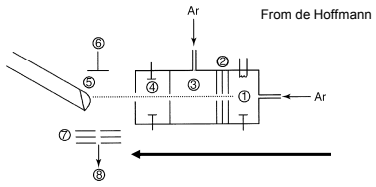


Figure 1.12
Diagram of a FAB gun. (1) Ionization of argon; the resulting ions are accelerated and focused by lenses (2). In (3), the argon ions exchange their charge with neutral atoms, thus becoming rapid neutral atoms. As the beam path passes between the electrodes (4), all ionic species are deflected. Only rapid neutral atoms reach the sample dissolved in a drop of glycerol (5). The ions ejected from the drop are accelerated by the pusher (6) and focused by electrodes (7) towards the analyzer (8)

SIMS primary **ions** are produced, e.g., as Cs atoms vaporize through a porous tungsten plug.

From SIMS Tutorial:
http://www.eaglabs.com/en-US/references/tutorial/simstheo/

Primary Beam of **neutrals** produced by ionizing and accelerating compound into charge exchange collision with neutral. e.g.:

$$Ar^{+}_{rapid} + Ar_{slow} \rightarrow Ar+_{slow} + Ar_{rapid}$$

Static SIMS

- **Low current** (10^{-10} A cm^2) of keV primary ions (Ar^+, Cs^+ ..) impact the **solid analyte surface**
- Low probability of area being struck by multiple ions; **less than 1/10 of atomic monolayer consumed**
- Primary ion beam focused to less than 1 um enables **high resolution mapping** – Often pulsed beam + TOFMS
- Sensitive technique for the **ID of organic molecules**
- Spectra show high abundance of protonated or cationized **molecular ions**.
- **Yields depend on substrate and primary beam**; as high as 0.1 ions per incident ion. Elemental yields vary over many orders of magnitude.

FAB and liquid-SIMS

- **Sample is dissolved in non-volatile liquid matrix** and bombarded with beam of neutrals (FAB) or ions
- **Shock wave ejects ions and molecules from solution.** Generally eject ions that already exist in solution.
- **Presence of charge (SIMS vs. FAB) has little effect on the desorption process**. Neutrals used out of convenience for coupling to some instruments.
- Use of liquid allows **high primary ion currents** while maintaining molecular ions
  - Solution presents mobile, constantly renewed surface to beam
- Disadvantage: substantial **background** of matrix (e.g., Glycerol) ions and matrix adducts.
- **Flow FAB:**
  - Continuous flow of liquid into mass spectrometer at rate of 1 – 20 uL/min
  - Allows more use of more volatile solvent (e.g., water, methanol, or acetonitrile)
  - Can be coupled to separation

Matrix Assisted Laser Desorption Ionization (MALDI)

- **Analyte molecules are embedded in a crystalline matrix** composed of a low molecular weight organic species.
- Dried mixture is struck with a short, intense laser pulse having a wavelength that is **strongly absorbed by the matrix** (often UV).
- Rapid heating of matrix causes sublimation and expansion into gas phase. **Intact analyte molecules carried with little internal energy**.
- Most widely accepted ionization mechanism is gas-phase **proton transfer**.
- **Efficient, "soft," and relatively universal** (wavelength independent of analyte). Matrix isolates analyte molecules, preventing clusters.
- Allows analysis of large (100s of kDa) intact biopolymers (2002 Nobel Prize)

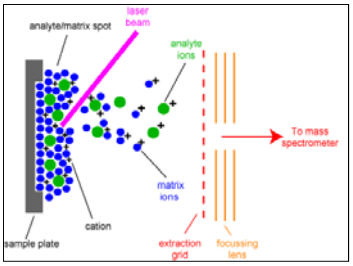


Image from: Univ. of Bristol
http://www.chm.bris.ac.uk/ms/theory/maldi-ionisation.html

Example of MALDI Data

- Spectra contain mostly single-charged ions.
- Fragmentation due to excess energy imparted on analyte during DI process is possible (Prompt, Fast, or Post Source)
- Optimized conditions determined empirically.

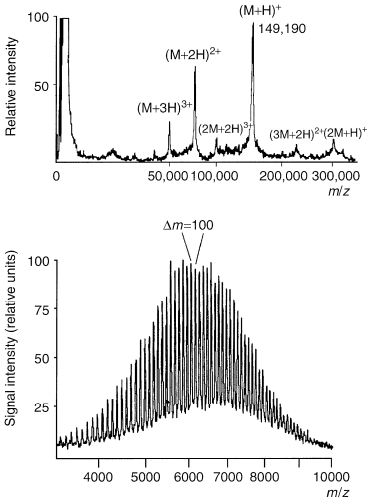


Figure 1.15
The MALDI spectra of a monoclonal antibody (*top*) and poly(methyl methoacrylate) of average mass 7100 Da (*bottom*) (Reproduced (modified) from Ref. 24 and from Finnigan MAT documentation, with permission)

From De Hoffmann

MALDI-TOF Mass Spectrometer

From Barker

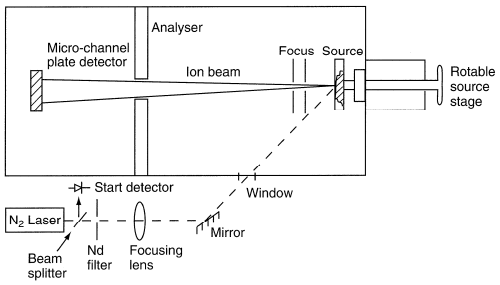


Figure 2.6a Schematic representation of a MALDI–TOF mass spectrometer

MALDI conveniently coupled to ToF-MS

1. Pulsed source, pulsed analyzer
2. Large m/z, large mass range

(See lab #1, HW #3, and next lecture)

Summary of DI Techniques

TABLE 13-14
Summary of Characteristics of DI methods

Sample type	Nonvolatile, thermally labile
Basic technique	Prompt delivery of energy to sample by energetic beam
Matrix	Organic liquid or solid; enhances ionization, minimizes fragmentation
Ionization mechanisms	Direct ion emission Cationization and ion-molecule reactions
Energy deposition	Broad; both a soft and a hard method
Ionization efficiency	10^{-1}% in FAB to 10^{-4}% in MALDI (sample can be recovered)
Mass range	10^4 Da (FAB–liquid SIMS) to 10^6 Da (MALDI)

From Lambert

Elemental Analysis Notes

- Need to decompose analyte into vapor-phase **ATOMS**
  - E.g. to determine isotope ratios
- Sources are also used by optical spectroscopy
  - MS tends to produce less complex signals, and can be more sensitive

Thermal Ionization

•**One of the earliest ionization techniques for MS.** Remains the most precise and accurate method in MS to determine isotope ratios of solid samples.

•**Sample may be gas phase, or deposited on filament surface**

•One or more filaments are heated to high T by passage of a current.

•**Electron transfer between atom and filament** produces intense, stable beams of positive and/or negative **atomic ions.**

•Multiply charged ions are not observed, and clusters are rare

•**Multiple filaments allows separate control of vaporization and ionization parameters**

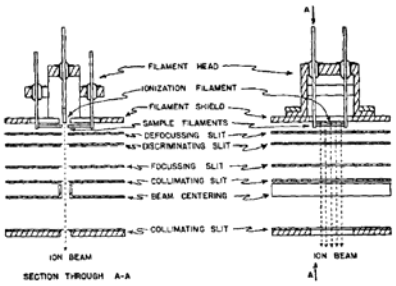


Figure from: Inghram and Chupka, *Rev Sci Inst*, 24, 518, 1953

Thermal Ionization (cont'd)

Ion yield range from 1 to 10% and depend on **electron affinity** of the analyte, the **work function** of the filament material, and the **temperature** of the filament. Work function may depend on treatment of filament surface. (See Heumann et al, *Analyst*, 120, 1291, 1995)

Positive Ions: compounds with low first ionization potentials; high work function filaments

Negative ions: High electron affinities; low work function filaments

Thermal ionization cavity source offers order of magnitudes improvements in efficiency.

Metal tube is heated by high energy electron bombardment.

As the sample evaporates inside the crucible, gaseous analyte atoms are produced which interact with the inner surface of the crucible walls to produce positive ions through surface ionization.

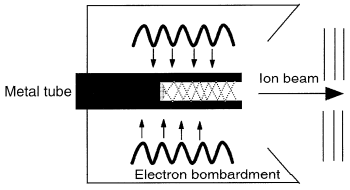


Figure 1.31
Schematic representation of a thermal ionization cavity source

From de Hoffmann

Spark Ionization Source

•Most transition metals difficult to ionize thermally. **Spark developed by Dempster to extend MS analysis to metals.**

•Pulsed 1-MHz RF-voltage of several kilovolts produces discharges between two rod electrodes.

•**Sample may serve as one electrode, or be mixed with carbon and placed in cup electrode**

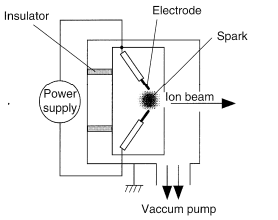
•**Ionization occurs within plasma.**

•Singly and multiply charged atomic ions, polymer ions, and heterogeneous compounds

•Intensity of major constituent peaks decreases with charge number.

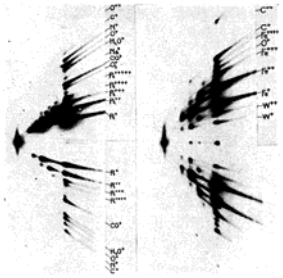
•**Approximately equal sensitivity for all elements.** Useful for analysis of trace impurities (DLs in ppb range).

• ↓ Ions have very wide energy distribution and the spark is subject to random fluctuations in intensity



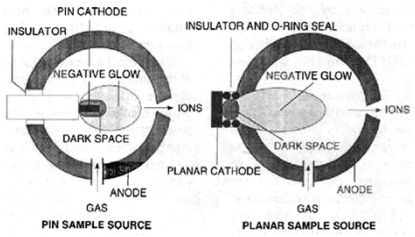
From de Hoffmann

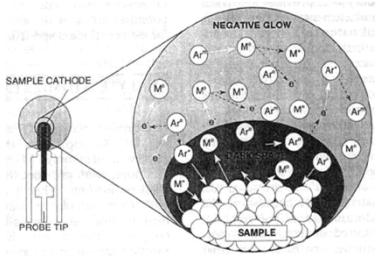
Figure 1.32
Typical spark ion source



From Dempster, *Rev Sci Inst*, 7, 46, 1936

Glow Discharge Source





From King, Teng, and Steiner, *J. Mass Spec.*, 30, 1061, 1995.

•Produces singly charged atomic cations. **Used primarily for bulk metal analysis.**

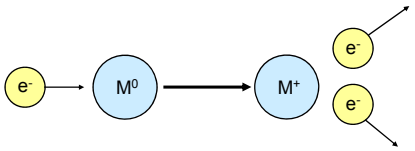
•**Discharge between cathode (sample) and anode in Ar** at low pressure (ca 0.1-10 Torr; 5 mm gap, 1 kV, 1-2 mA)

•**Sputtering:** Ions and electrons from plasma accelerate toward electrodes. Ar^+ attacks cathode surface, releasing M (neutral) and M^+

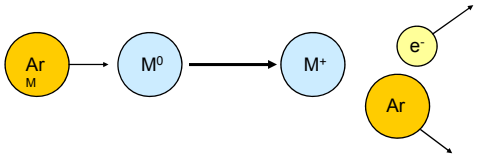
•80% of potential drop occurs in non-luminous "dark space" (cathode fall) extending 1 mean free path from cathode. M^+ produced by sputtering cannot escape this region. **Effectively decoupling atomization and ionization steps and reducing matrix effects on ionization.**

•**Collisions and ionization abound in "Negative Glow."** **Neutral M ionized by multiple pathways.**

GD: Collisional Ion Formation Processes



Electron Ionization



Penning Ionization

Within Negative Glow, electron ionization and Penning Ionization account for 90% of the observed M^+.

Penning Ionization

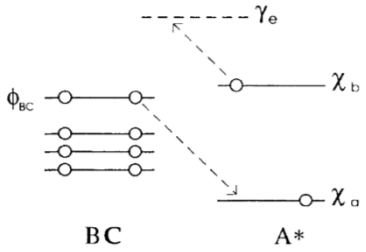


Fig. 1. The electron-transfer process in Penning ionization.

From: Faubert et al, IJMS, 1993, 69-77

$A^* + BC \longrightarrow A + BC^+ + e^-$

OR

$A^* + BC \longrightarrow A + B^+ + C + e^-$

Electron transfer reaction

Occurs if ionization potential of BC is less than excited state energy of A^*

Inductively Coupled Plasma

•ICP source was originally developed for Atomic Emission Spectroscopy of solutions.

•ICP-MS is capable of trace multielement analysis of **solids or liquids**, often at the part per trillion level.

•Can detect all elements except F, Ne, and He. Ionization efficiency >= 90% for 54 elements.

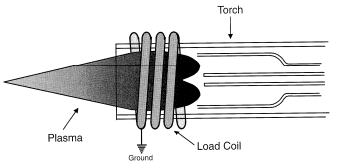


FIGURE 3.1 Plasma with torch assembly and load coil.

Hardware:

3 concentric quartz tubes. Argon flowing through each at atmospheric pressure.

Cooled induction coil surrounds the top of largest tube – powered by RF Generator.

An Initial Tesla sparks ionizes flowing argon.

RF field accelerates these ions, leading to collisions and more ions. Equilibrium between ionization and recombination.

Plasma reaches 10 000 K.

Photo from: http://ewr.cee.vt.edu/environmental/teach/smprimer/icpms/icpms.htm

ICP Source

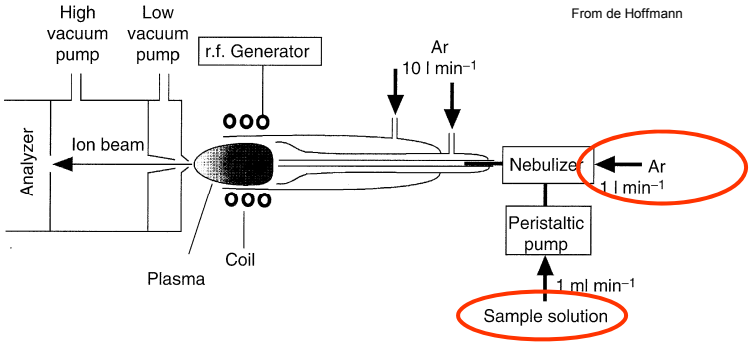


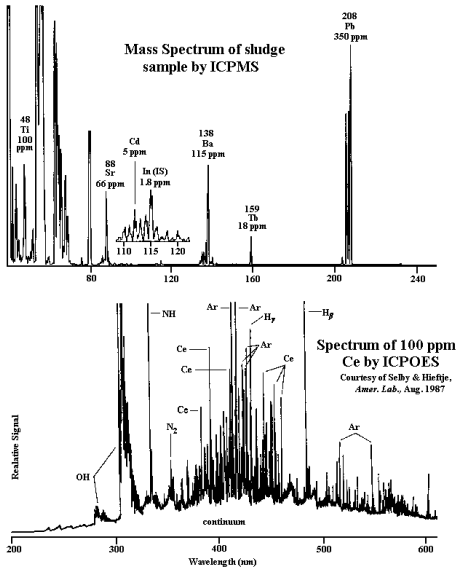
Figure 1.34
Schematic diagram of an inductively coupled plasma source

•Sample (vapor or droplet) carried into plasma through central tube.

•**High T desolvates, vaporizes, atomize, and ionize sample – Close to 100% efficiency.**

•As for other atmospheric pressure ionization sources, transfer to MS **requires differentially pumped interface.**

ICP-MS vs. ICP-OES



- **MS much simpler** than the optical emission spectra Most heavy elements exhibit hundreds of emission lines, but they have only 1-10 natural isotopes in the mass spectrum.
- ICP-OES suffers from many overlapping **spectral interferences** from other elements and a very **high background emission** from the plasma itself, limiting detection limits.
- **Detection limits of ICP-MS are three orders of magnitude better** than ICP-OES.

Comparison of Molecular Ionization Techniques

Table 2.3. Comparison of various ionization methods

Ionization Method	Ion Type	Sample Type	Separation Technique
EI	$M^{+\cdot}$, fragments	Nonpolar and some polar organic compounds	GC
CI	$[M+H]^+$, $[M-H]^-$, $M^{-\cdot}$	Nonpolar and some polar organic compounds	GC
Thermospray	$[M+H]^+$, $[M-H]^-$, $[M+NH_4]^+$	Polar compounds	LC
FAB	$[M+H]^+$, $[M-H]^-$	Peptides, proteins, lipids, carbohydrates, oligosaccharides, nucleotides, oligonucleotides	LC, CE
APCI	$[M+H]^+$, $[M-H]^-$	Polar compounds, drugs	LC
ESI	$[M+nH]^{n-}$, $[M-nH]^{n-}$	Peptides, proteins, lipids, carbohydrates, oligosaccharides, oligonucleotides	LC, CE
MALDI	$[M+H]^+$, $[M-H]^-$	Peptides, proteins, lipids, carbohydrates, oligosaccharides, oligonucleotides	LC, CE

Desorption Ionization Summary

TABLE 13-11
Procedures Used in Desorption Ionization

Ionization Method	*Energy Source*	*Flux*	*Matrix*	*Mass Analyzer*	*Comments*
Static secondary ion MS (SIMS)	keV ions	10^{-10} A cm^{-2} (Ar^+, Cs^+, etc.)	None, solid	Any	Surface sensitive, nondestructive, low signal
Liquid SIMS	keV ions	10^{-6} A cm^{-2} (10^{13} ions cm^{-2} s^{-1}) (Cs^+, etc.)	Liquid	Any	Higher, longer lasting signal
Fast atom bombardment (FAB)	keV atoms	10^{13} atoms cm^{-2} s^{-1} (Xe atoms)	Liquid	Any	High, long-lasting signal, high background
Plasma desorption (PD)	MeV ions	10^3 particles cm^{-2} s^{-1}	Nitrocellulose	Time-of-flight	High ionization efficiency, low signals
Laser desorption (LD) and matrix-assisted laser desorption (MALDI)	Photons	$\geq 10^6$ watt cm^{-2}	Solid matrix absorbs radiation in MALDI	Usually time-of-flight	CW lasers can cause thermal degradation

From Lambert