



# Radiochemistry Webinars Nuclear Materials Analysis– Mass Spectrometry



*In Cooperation with our University Partners*



UNIVERSITY of CALIFORNIA • IRVINE



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# Meet the Presenter...

*Dr. R. Kenneth Marcus*



Dr. Marcus has been a Professor of Analytical Chemistry at Clemson University since 1986. His undergraduate education included BS degrees in Chemistry and Physics from Longwood College (now University) in Farmville, VA, in 1982. He received his Ph.D. in Analytical Chemistry in 1986 from the University of Virginia, where he worked for Prof. W. W. Harrison. His current research program covers two distinct lines of study: use of capillary-channeled polymer (C-CP) fibers and films as platforms for protein separations, and development of liquid sampling-atmospheric pressure glow discharge (LS-APGD) microplasmas for spectrochemical analysis. The latter research earned Dr. Marcus the 2015 Lester Strock Award from the Society for Applied Spectroscopy. His research program is funded by the National Science Foundation, DTRA, and the Pacific Northwest and Savannah River National Laboratories. His research group has published over 180 refereed journal articles, made over 550 conference presentations (>130 invited), and yielded over a dozen U.S. patents. He serves on the editorial advisory boards of Spectrochimica Acta B, the Journal of Analytical Atomic Spectrometry, and Analytical and Bioanalytical Chemistry. Dr. Marcus takes great pride in the fact that over half of his 34 Ph.D. graduates are employed in federal laboratories including NIST, the CDC, and the Savannah River, Oak Ridge, Sandia, Los Alamos, and Pacific Northwest National Laboratories. Dr. Marcus has been honored as a Fellow of the Royal Society of Chemistry and the American Association for the Advancement of Science.

**Contact Information: [marcusr@clemson.edu](mailto:marcusr@clemson.edu)**



# Nuclear Material Analysis

## Mass Spectrometry

Dr. R. Kenneth Marcus  
Clemson University



National Analytical Management Program (NAMP)  
U.S. Department of Energy Carlsbad Field Office

TRAINING AND EDUCATION SUBCOMMITTEE



# Introduction part I - Why mass spectrometry ?

- Complete elemental coverage (H - to - ...)
- High sensitivity (low LODs)
- Quantitative analysis
- Relatively uniform figures of merit
- Isotope ratios: all the isotopes, all the time . . . .
- No need for multiple methods ( $\alpha$ ,  $\gamma$ , n. . .)
- **No requirement that analyte be “activated”**
- Only a few “peaks” per element
- On-line coupling with chemical processing
- Wide diversity of approaches, as dictated by specific challenges
  - Solids, liquids, or gases
  - Elemental analysis or isotopic determinations
  - Identification of chemical species

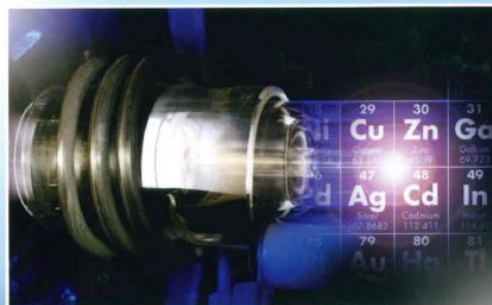
# Introduction part II - Why not mass spectrometry (real and perceived)?

- Too many choices
- Too many experimental variables
- Very high levels of user expertise
- Too much sample prep
- It is destructive
- Vacuum systems, high voltages, weight
- . . . . .

Just like anything else, at the end of the day a cost/benefit analysis must be done . . . .

Mass spectrometry provides more bang for your buck than any other analytical technique ! !

*Johanna Sabine Becker*



# *Inorganic Mass Spectrometry*

*Principles and Applications*

 WILEY

# Isotopes of selected elements

**Table 22-1** Isotopes of selected elements

Element	Mass number	Mass (Da) <sup>a</sup>	Abundance (atom %) <sup>b</sup>	Element	Mass number	Mass (Da) <sup>a</sup>	Abundance (atom %) <sup>b</sup>
Proton	1	1.007 276 467	—	Cl	35	34.968 85	75.78
Neutron	1	1.008 664 916	—		37	36.965 90	24.22
Electron	—	0.000 548 580	—	Ar	36	35.967 55	0.336
H	1	1.007 825	99.988		38	37.962 73	0.063
	2	2.014 10	0.012		40	39.962 38	99.600
B	10	10.012 94	19.9	Fe	54	53.939 61	5.845
	11	11.009 31	80.1		56	55.934 94	91.754
C	12	12 (exact)	98.93		57	56.935 40	2.119
	13	13.003 35	1.07		58	57.933 28	0.282
N	14	14.003 07	99.632	Br	79	78.918 34	50.69
	15	15.000 11	0.368		81	80.916 29	49.31
O	16	15.994 91	99.757	I	127	126.904 47	100
	17	16.999 13	0.038	Hg	196	195.965 81	0.15
	18	17.999 16	0.205		198	197.966 75	9.97
F	19	18.998 40	100		199	198.968 26	16.87
Si	28	27.976 93	92.230		200	199.968 31	23.10
	29	28.976 49	4.683		201	200.970 29	13.18
	30	29.973 77	3.087		202	201.970 63	29.86
P	31	30.973 76	100		204	203.973 48	6.87
S	32	31.972 07	94.93	Pb	204	203.973 03	1.4
	33	32.971 46	0.76		206	205.974 45	24.1
	34	33.967 87	4.29		207	206.975 88	22.1
	36	35.967 08	0.02		208	207.976 64	52.4

a. 1 dalton (Da) = 1/12 of the mass of  $^{12}\text{C}$  =  $1.660\,538\,73 \times 10^{-27}$  kg. [Data from G. Audi and A. H. Wapsta, *Nucl. Phys.* **1995**, A595, 409 found at [www.dne.bnl.gov/CoN/index.html](http://www.dne.bnl.gov/CoN/index.html). This source provides more significant figures for atomic mass than are cited in this table.]

b. Abundance is representative of what is found in nature. Significant variations are observed. For example, the  $^{18}\text{O}$  content of natural substances has been found in the range 0.087 7 to 0.221 7 atom %. [Data from K. J. R. Rosman and P. D. P. Taylor, "Isotopic Compositions of the Elements 1997," *J. Phys. Chem. Ref. Data* **1998**, 27, 1275.]



**Table 9.36** Application fields for determination of natural and artificial long-lived radionuclides (LLR).

Application field	Purpose/Materials	Radionuclides
Environmental monitoring	<i>Study of natural radioactivity</i> – in sea, river and rain water, plants, animals, soils,	U and Th (natural)
	<i>Contamination of environment (artificial radionuclides)</i> – nuclear power plants and accidents – nuclear weapons and weapon tests (e.g., nuclear fallout)	Tc, <sup>90</sup> Sr, <sup>129</sup> I, Np, Pu, Th, U, Am, Cm, Ra <sup>236</sup> U/ <sup>238</sup> U, <sup>240</sup> Pu/ <sup>239</sup> Pu
Solid-state research	<i>Material control of natural radioactivity</i> in high purity metals, semiconductors, ceramics	U and Th impurities
Geology	<i>Dating of geological samples</i> – rocks and minerals	<sup>87</sup> Rb– <sup>87</sup> Sr, <sup>147</sup> Sm– <sup>143</sup> Nd, <sup>187</sup> Re– <sup>187</sup> Os, <sup>238</sup> U– <sup>206</sup> Pb
Health control	<i>Control of exposed and contaminated persons</i> working in nuclear power plants or other nuclear facilities (nuclear laboratories in research and medicine) and of persons living in contaminated areas – in urine, blood, faeces, – in tissue, hair, nails	e.g., Th, U, Pu, <sup>90</sup> Sr, Am, Np, Cm
Food control	drinking, mineral waters, foods	U, Th, Pu, Ra
Isotope dilution techniques	<i>Quantification of analytical data</i>	e.g., iodine determination using <sup>129</sup> I
Tracer experiments	<i>Process control</i> – any material	
Radioactive waste control	<i>Characterization of waste</i> – nuclear facilities (e.g., nuclear reactor and power plants), – nuclear weapons, medicine <b>for recycling and final storage of radioactive waste</b>	e.g., <sup>129</sup> I, <sup>79</sup> Se, <sup>236</sup> U, Pu, transuranics

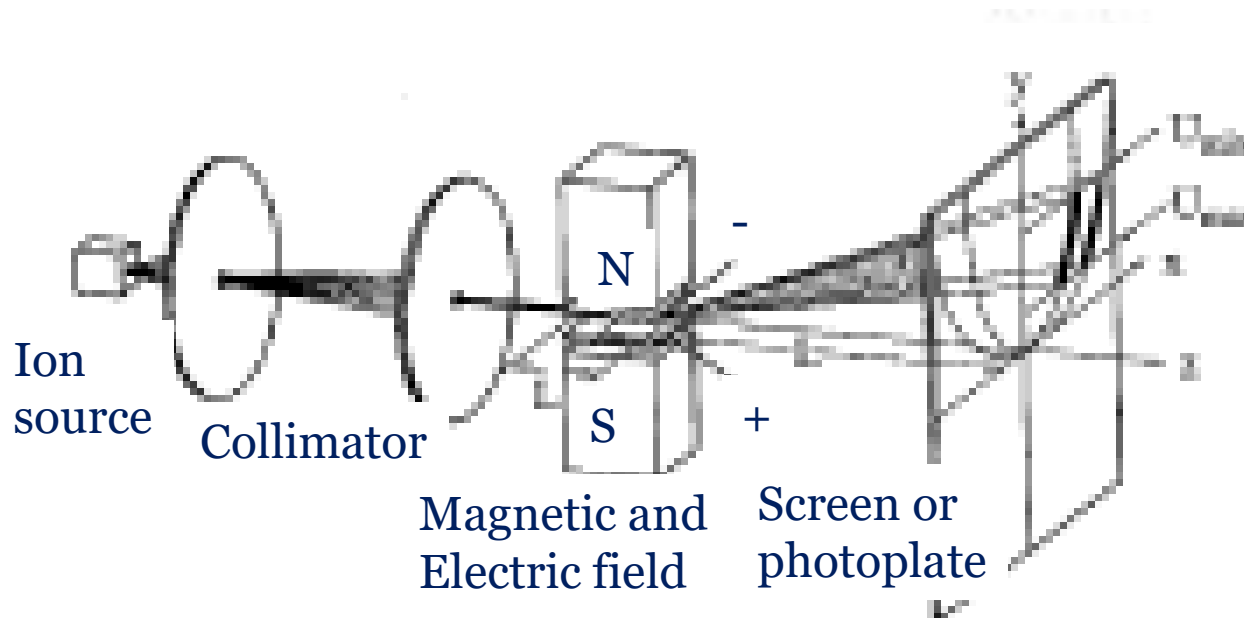


**Table 9.37** Most important radionuclides investigated by mass spectrometry.

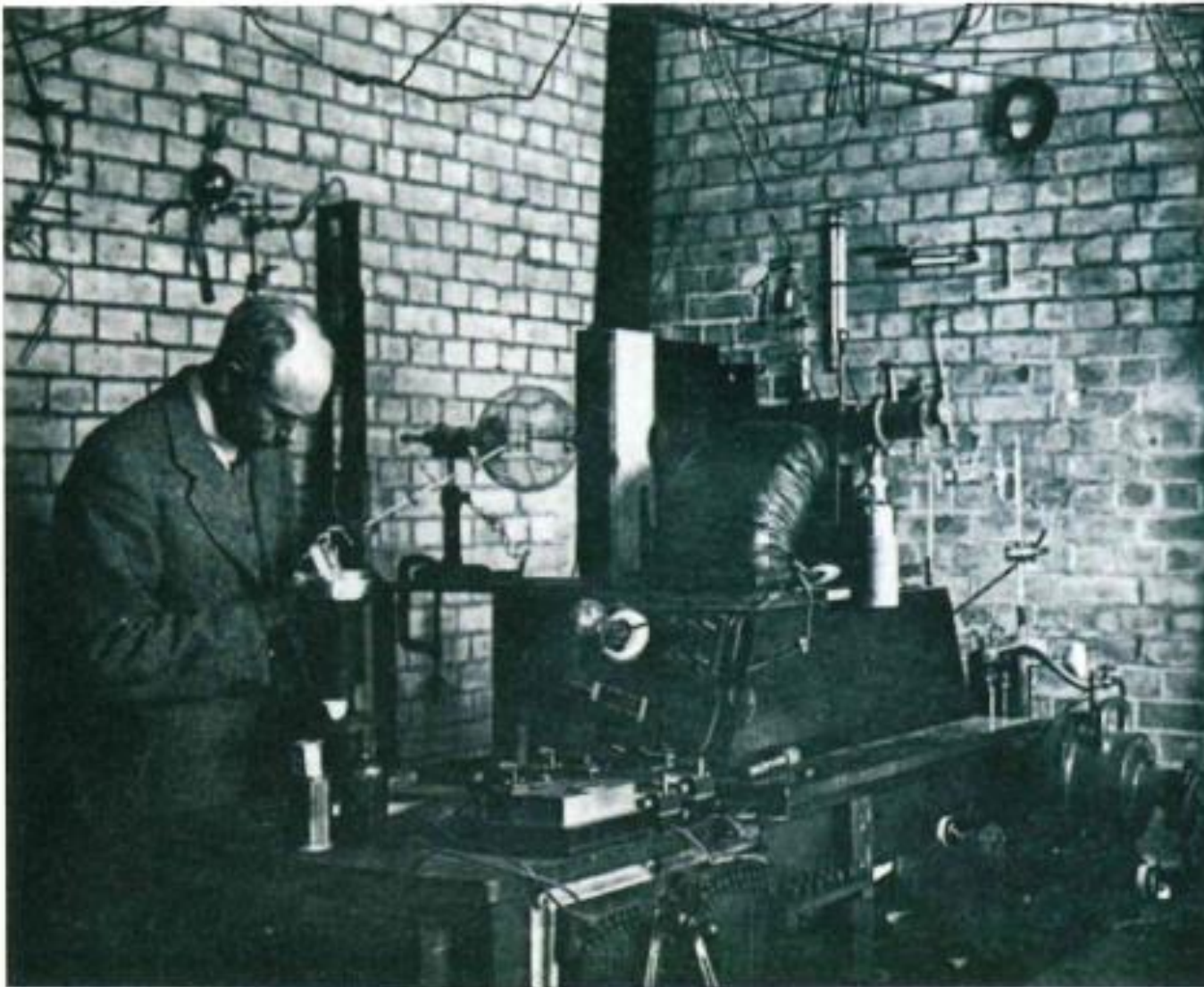
Radionuclide	Mass (u)	Half-life ( $t_{1/2}$ , a)	Mode of decay
$^{79}\text{Se}$	78.91850	$2.9 \times 10^5$	$\beta^-$ to $^{79}\text{Br}$
$^{90}\text{Sr}$	89.90774	29.1	$\beta^-$ to $^{90}\text{Y}$
$^{99}\text{Tc}$	98.90700	$2.13 \times 10^5$	$\beta^-$ to $^{99}\text{Ru}$
$^{129}\text{I}$	128.90499	$1.57 \times 10^7$	$\beta^-$ to $^{129}\text{Xe}$
$^{210}\text{Pb}$	209.98417	22.6	$\beta^-$ to $^{210}\text{Bi}$ ; $\alpha$ to $^{206}\text{Hg}$
$^{226}\text{Ra}$	226.02540	$1.6 \times 10^3$	$\alpha$ to $^{222}\text{Ra}$
$^{228}\text{Ra}$	228.03106	5.76	$\beta^-$ to $^{228}\text{Ac}$
$^{230}\text{Th}$	230.03313	$7.54 \times 10^4$	$\alpha$ to $^{226}\text{Ra}$ , SF
$^{232}\text{Th}$	232.03805	$1.4 \times 10^{10}$	$\alpha$ to $^{228}\text{Ra}$ , SF
$^{233}\text{U}$	233.03963	$1.59 \times 10^5$	$\alpha$ to $^{229}\text{Th}$ , SF
$^{234}\text{U}$	234.04095	$2.45 \times 10^5$	$\alpha$ to $^{230}\text{Th}$ , SF
$^{235}\text{U}$	235.04394	$7.04 \times 10^8$	$\alpha$ to $^{231}\text{Th}$ , SF
$^{236}\text{U}$	236.04556	$2.34 \times 10^7$	$\alpha$ to $^{232}\text{Th}$ , SF
$^{237}\text{Np}$	237.04817	$2.14 \times 10^6$	$\alpha$ to $^{233}\text{Pa}$ , SF
$^{238}\text{U}$	238.05078	$4.47 \times 10^9$	$\alpha$ to $^{234}\text{Th}$ , SF
$^{238}\text{Pu}$	238.04955	87.74	$\alpha$ to $^{234}\text{U}$ , SF
$^{239}\text{Pu}$	239.05216	$2.41 \times 10^4$	$\alpha$ to $^{235}\text{U}$ , SF
$^{240}\text{Pu}$	240.05381	$6.54 \times 10^3$	$\alpha$ to $^{236}\text{U}$ , SF
$^{241}\text{Pu}$	241.05684	14.29	$\alpha$ to $^{237}\text{U}$ ; SF, $\beta^-$ to $^{241}\text{Am}$
$^{242}\text{Pu}$	242.05874	$3.76 \times 10^5$	$\alpha$ to $^{238}\text{U}$ , SF
$^{244}\text{Pu}$	244.06420	$8.2 \times 10^7$	$\alpha$ to $^{240}\text{U}$ , SF
$^{241}\text{Am}$	241.05682	432.7	$\alpha$ to $^{237}\text{Np}$ , SF

SF – spontaneous fission.

# Mass Spectrometry: Gen-1

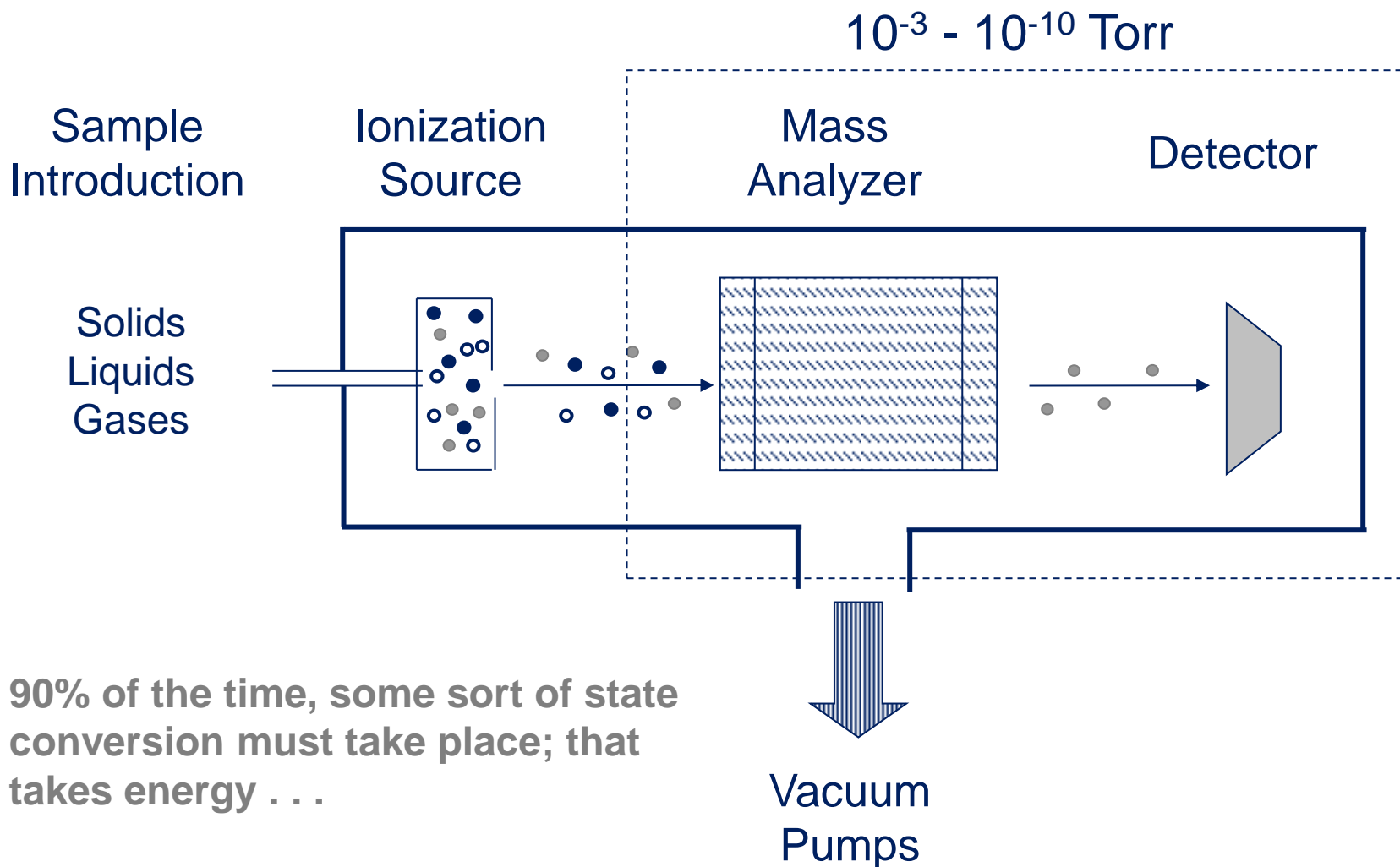


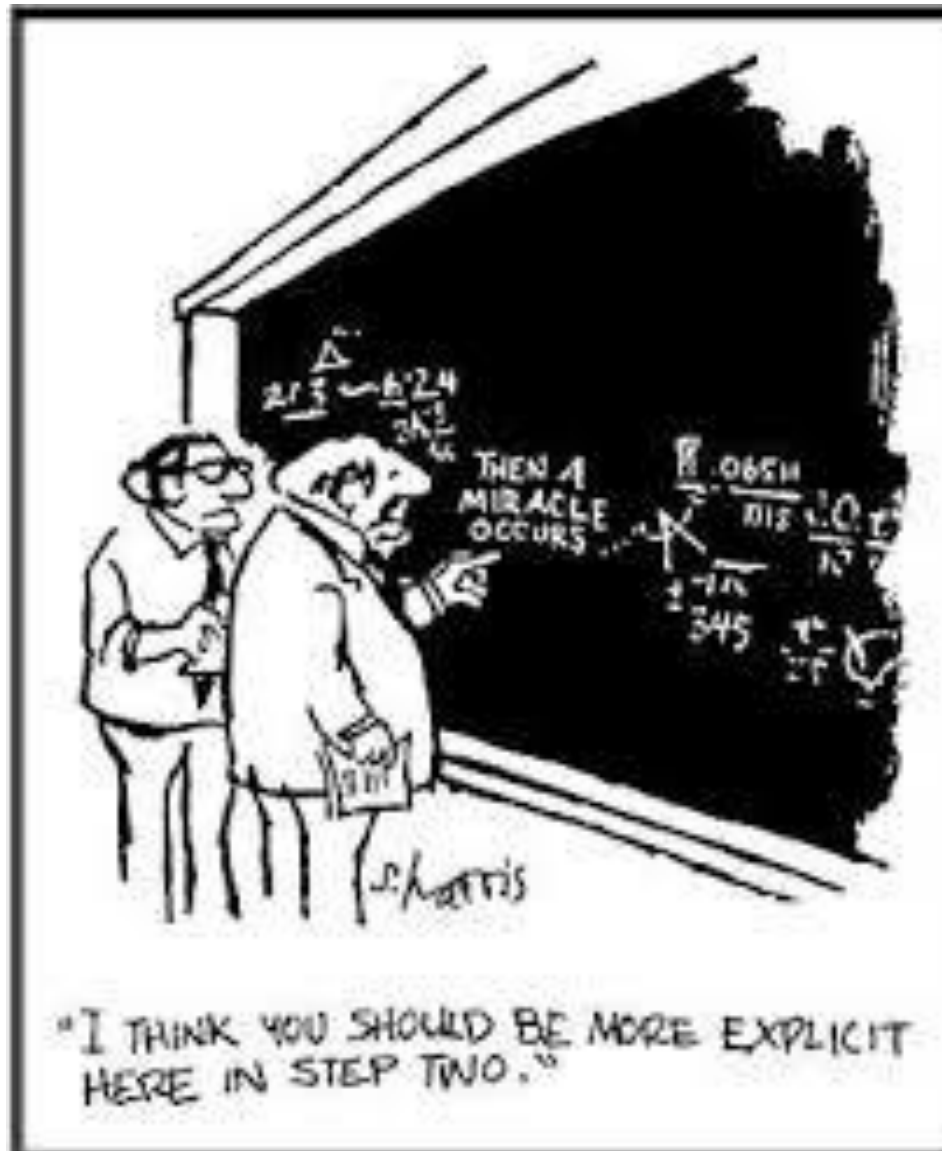
Parabola mass spectrograph constructed by J. J. Thomson (1910) with a discharge tube as ion source, a superimposed electrical field and a magnetic field oriented parallel to it for ion separation and a photoplate for ion detection



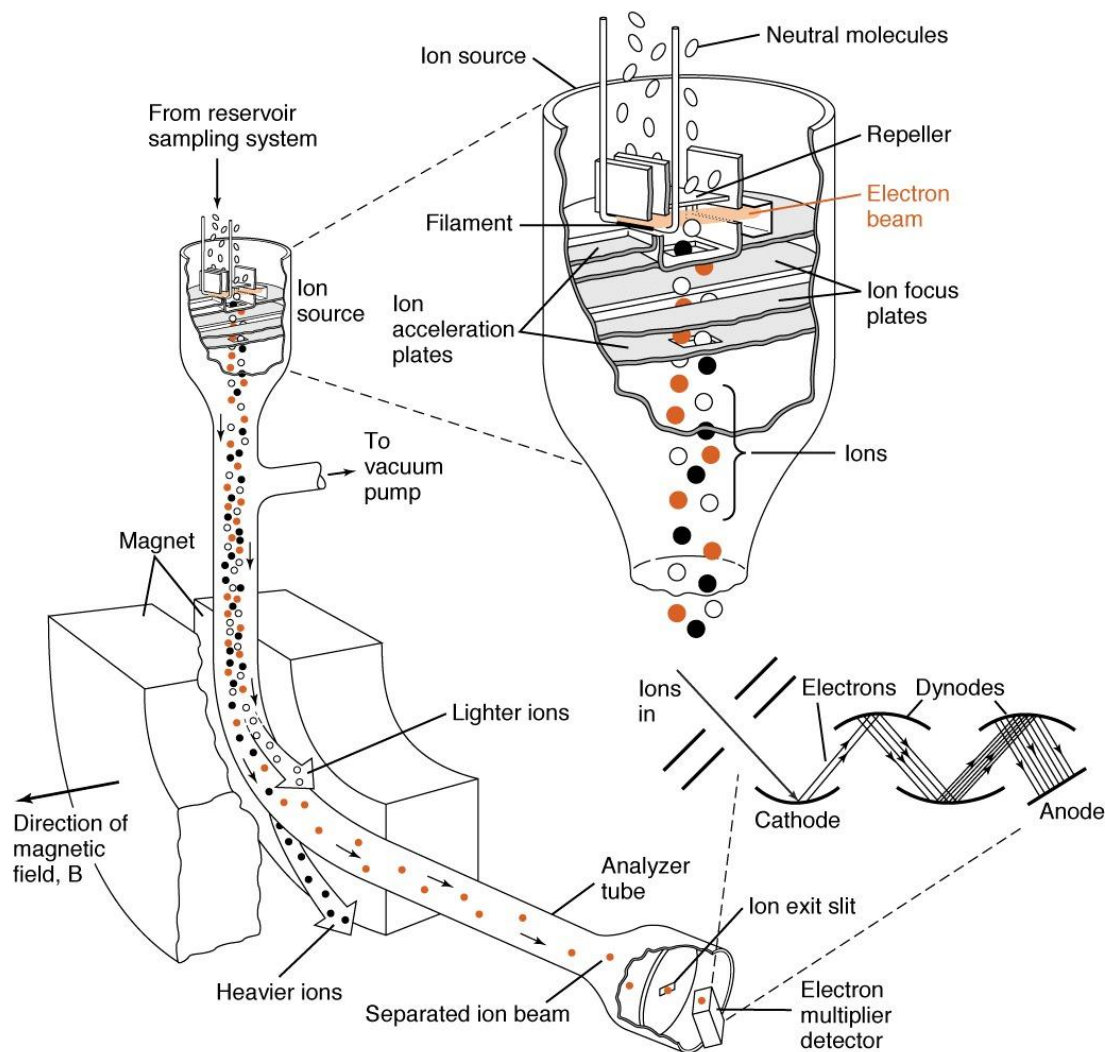
*Figure 1.11 F. W. Aston with second mass spectrograph (1922).*

# Basic anatomy of a mass spectrometer





# A simple example . . . .



# So, where are we going . . . ?

- Simple physics
- Mass analyzer types and figures of merit
- Spectrometer systems
- Ionization sources
- Methods of quantification
- Isotope ratio mass spectrometry

All in an hour ! ! !



# Simple Newtonian Physics

Opposite charges attract; like charges repel

Kinetic energy

$$KE = 1/2 mv^2 = zeV$$

Force

$$F = ma$$

Centrifugal force

$$F_C = (mv^2)/r$$

Centripetal force

$$F_M = Bzev$$

Time-of-flight

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

Cyclotron frequency

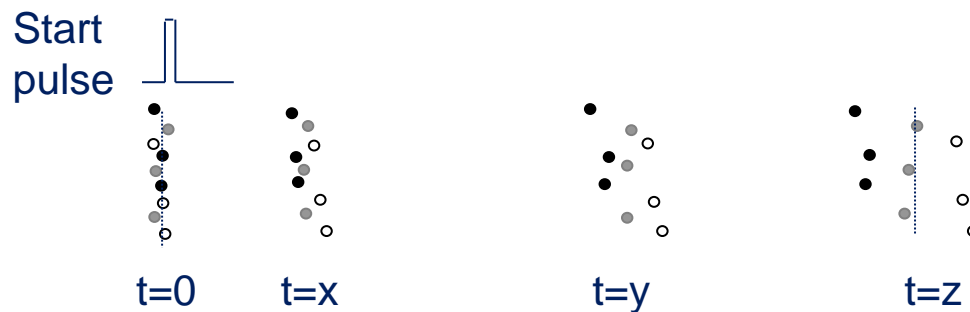
$$\omega_c = 1.537 \times 10^7 (zB/m)$$

Rule of Practicality: Vacuum pumps and power supplies cost money, add weight and complexity

# Mass Spectrometer Figures of Merit

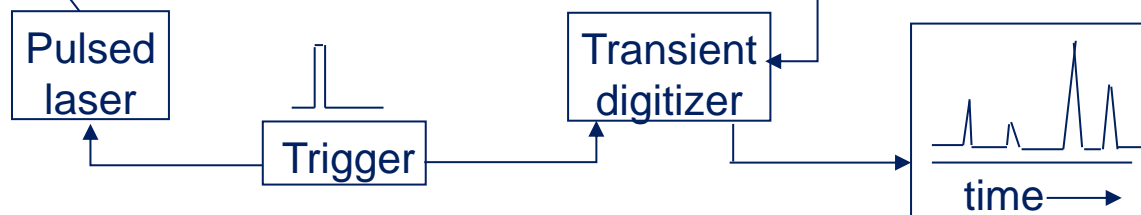
- Mass range
- Mass resolution ( $m/\Delta m$ )
- Scan speed
- Native sensitivity
- Ion source acceptability
- Operational overhead
  - Operating pressure
  - Power/space requirements
  - User sophistication
  - Transportability

# Time of flight (ToF) MS: the ion dash

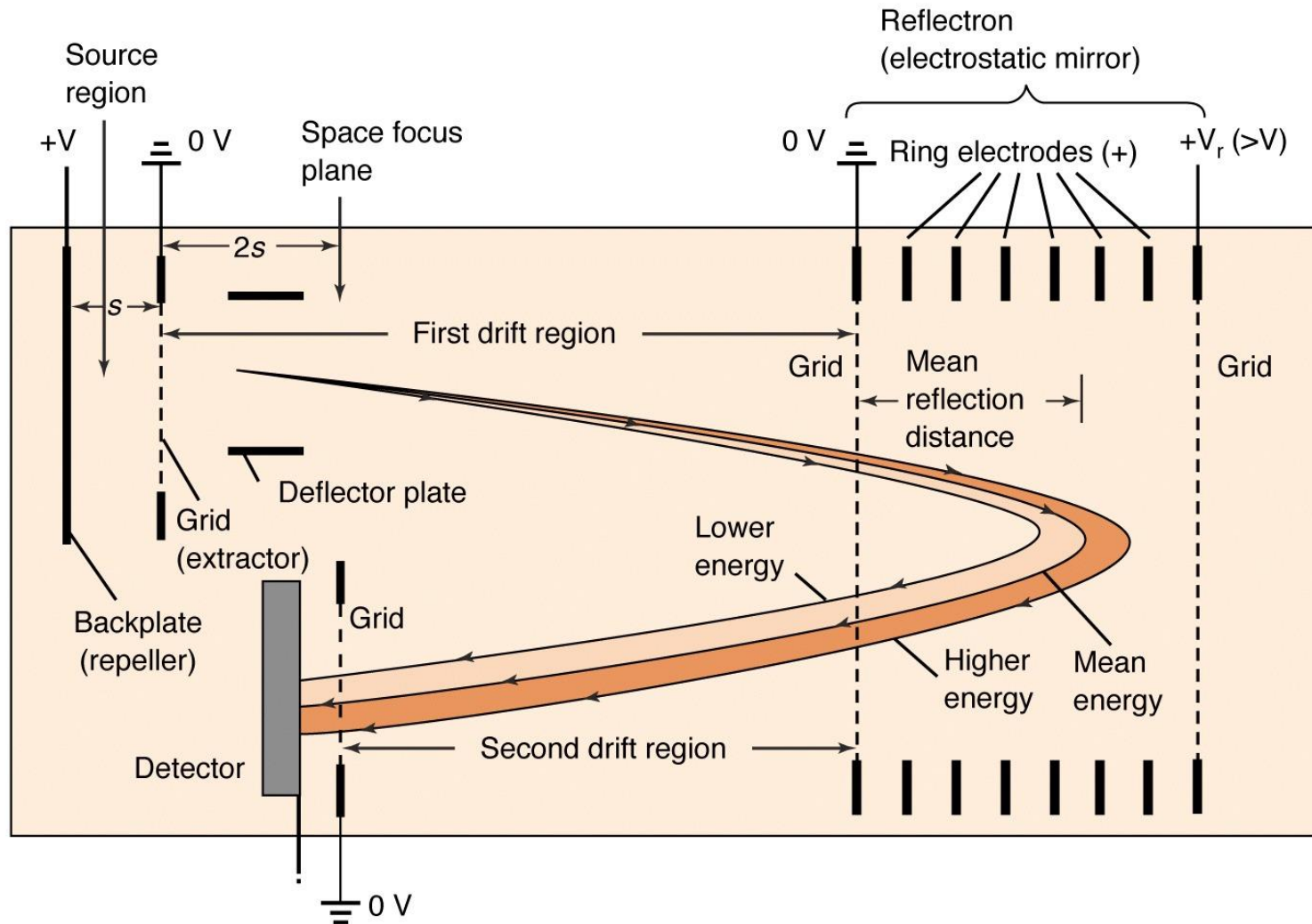


$$KE = zeV = \frac{1}{2} mv^2$$

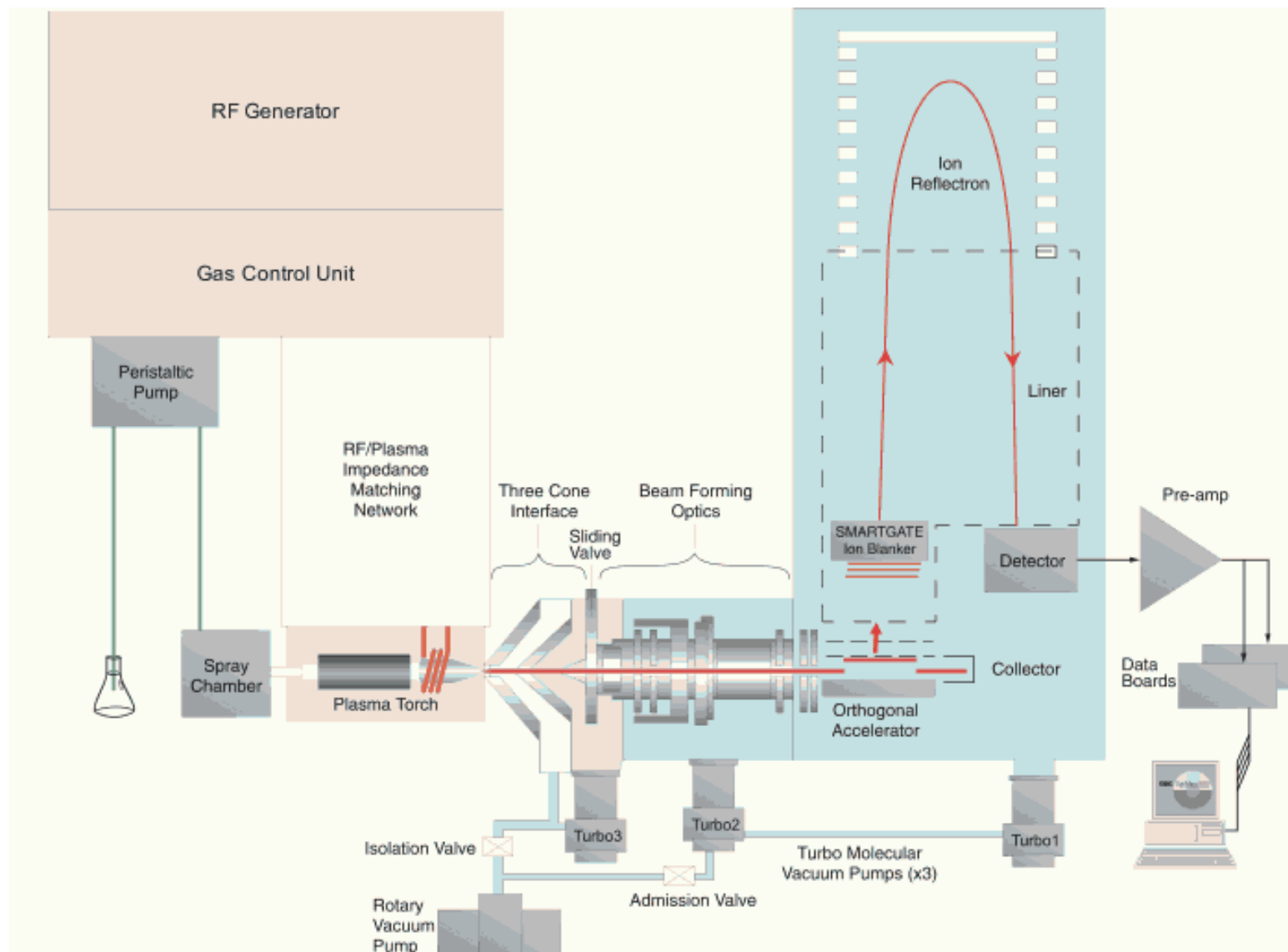
$$t = [m/(2zeV)]^{1/2}L$$



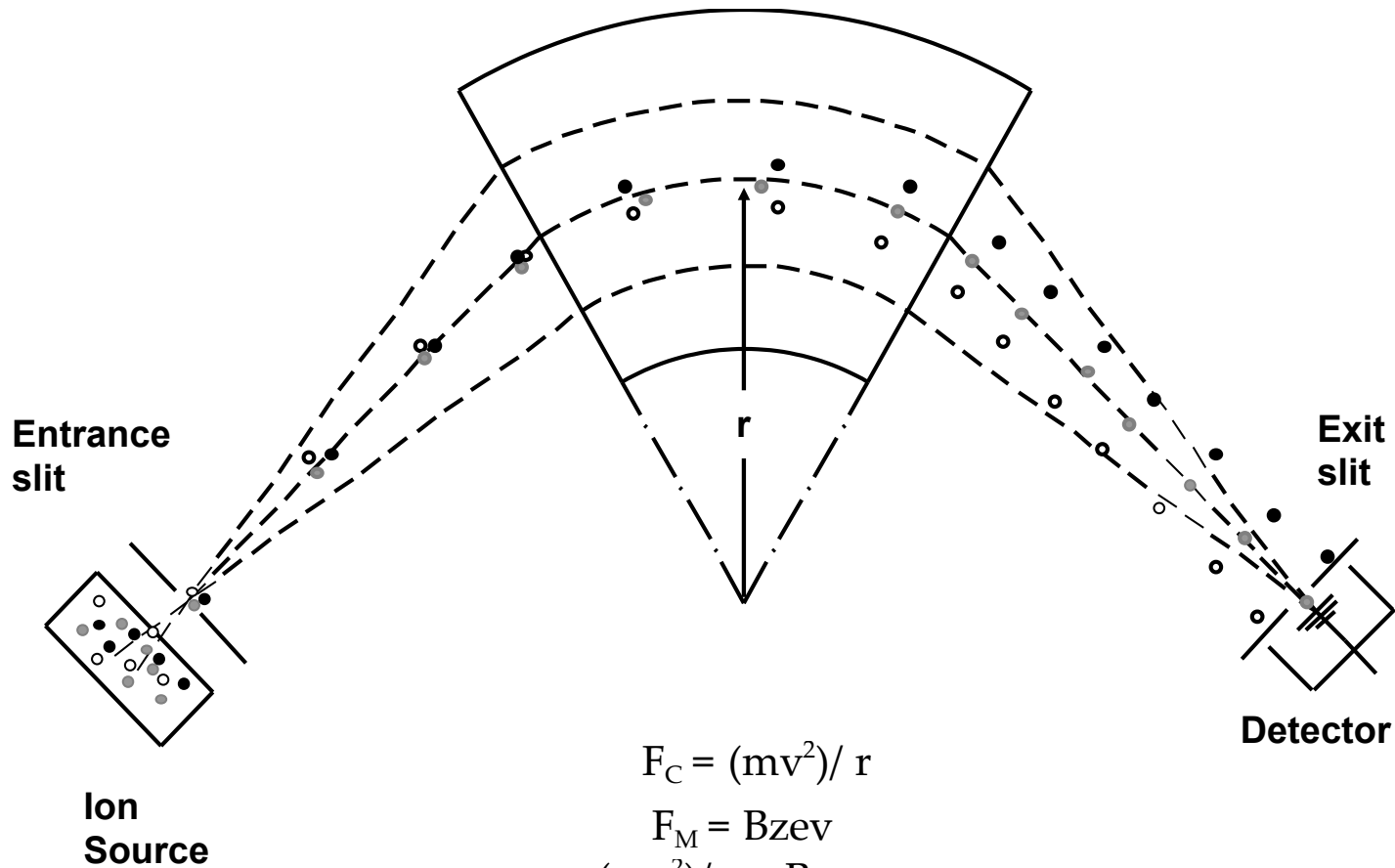
# Most ToFs employ reflectron technology . . .



# ICP-ToF-MS



# Electromagnets



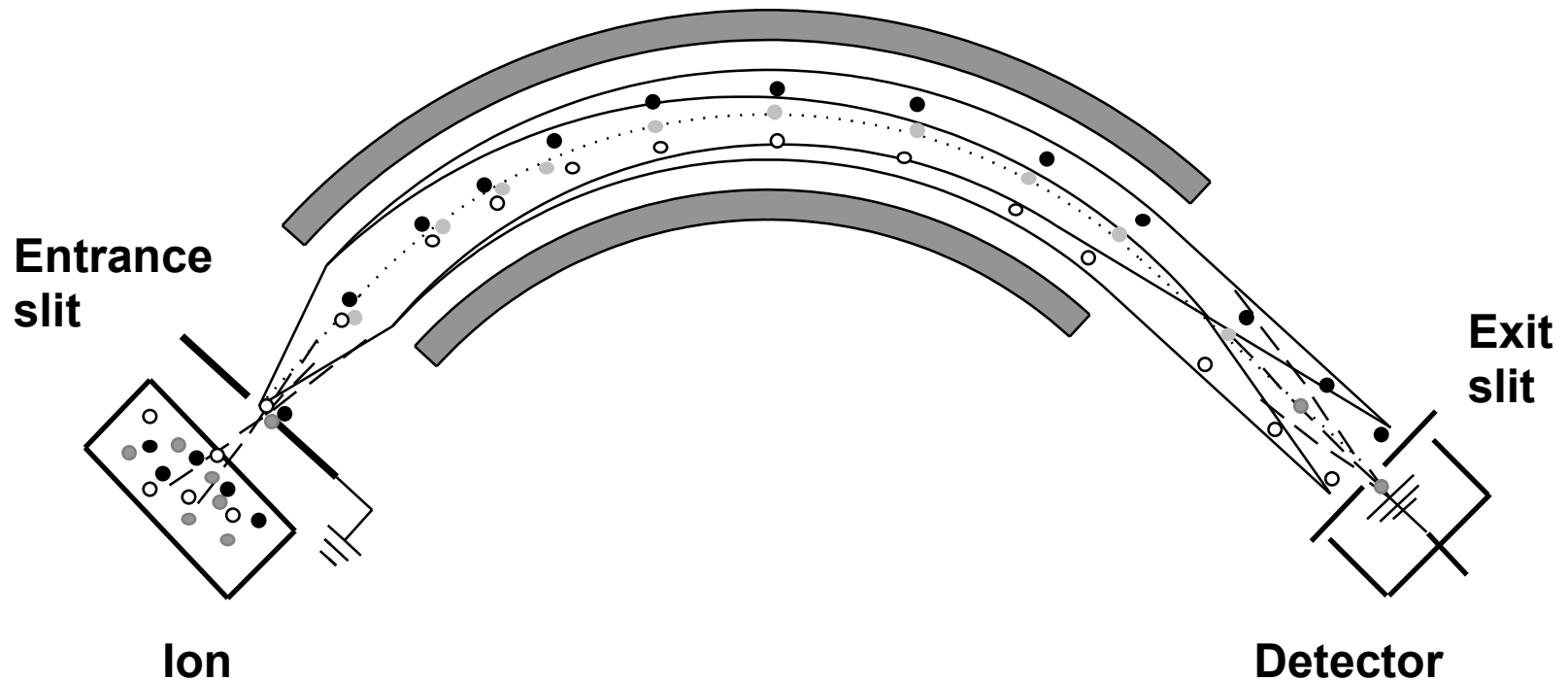
$$F_C = (mv^2)/r$$

$$F_M = Bzev$$

$$(mv^2)/r = Bzev$$

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

# Electrostatic analyzer

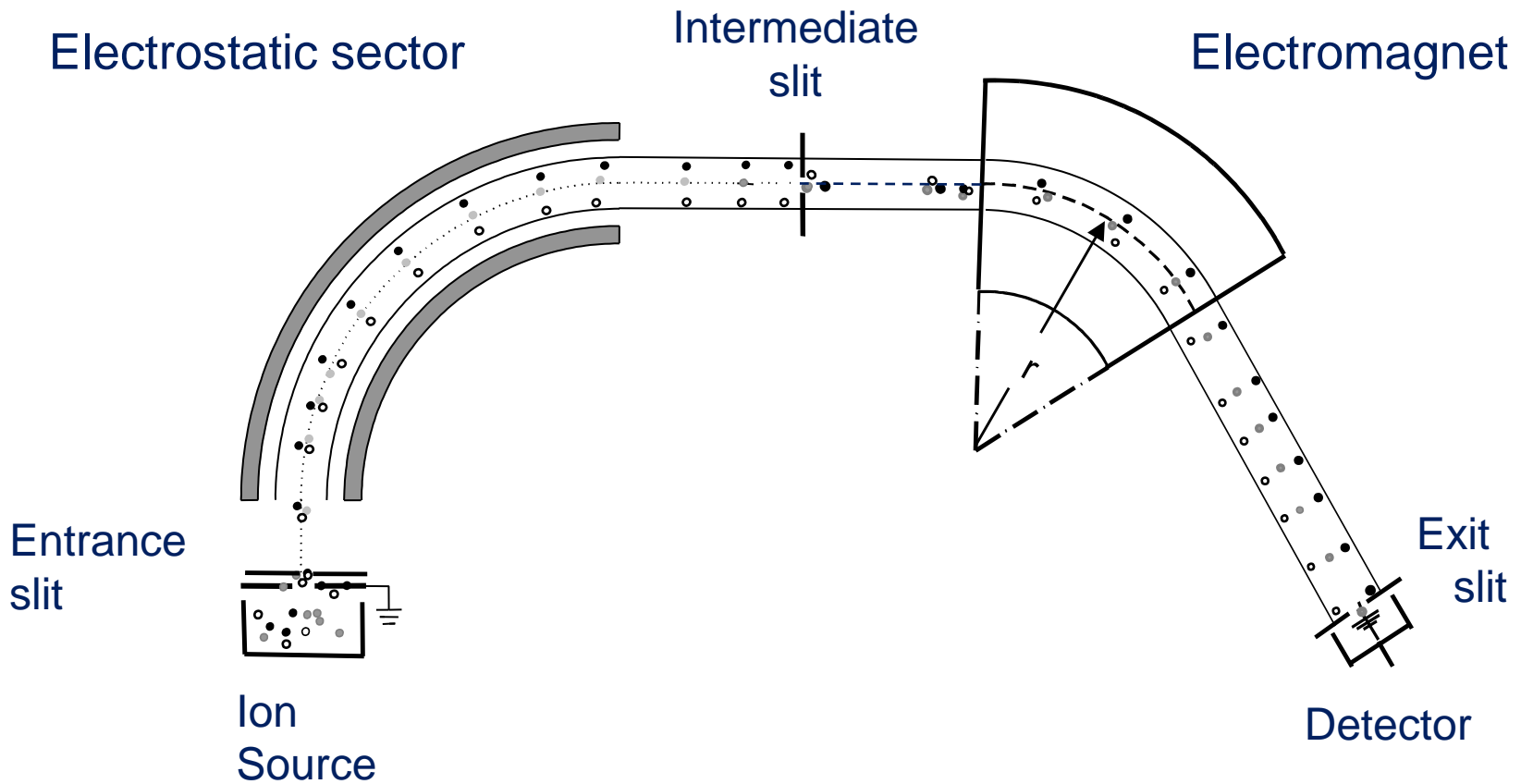


**Ion  
Source**

**Detector**

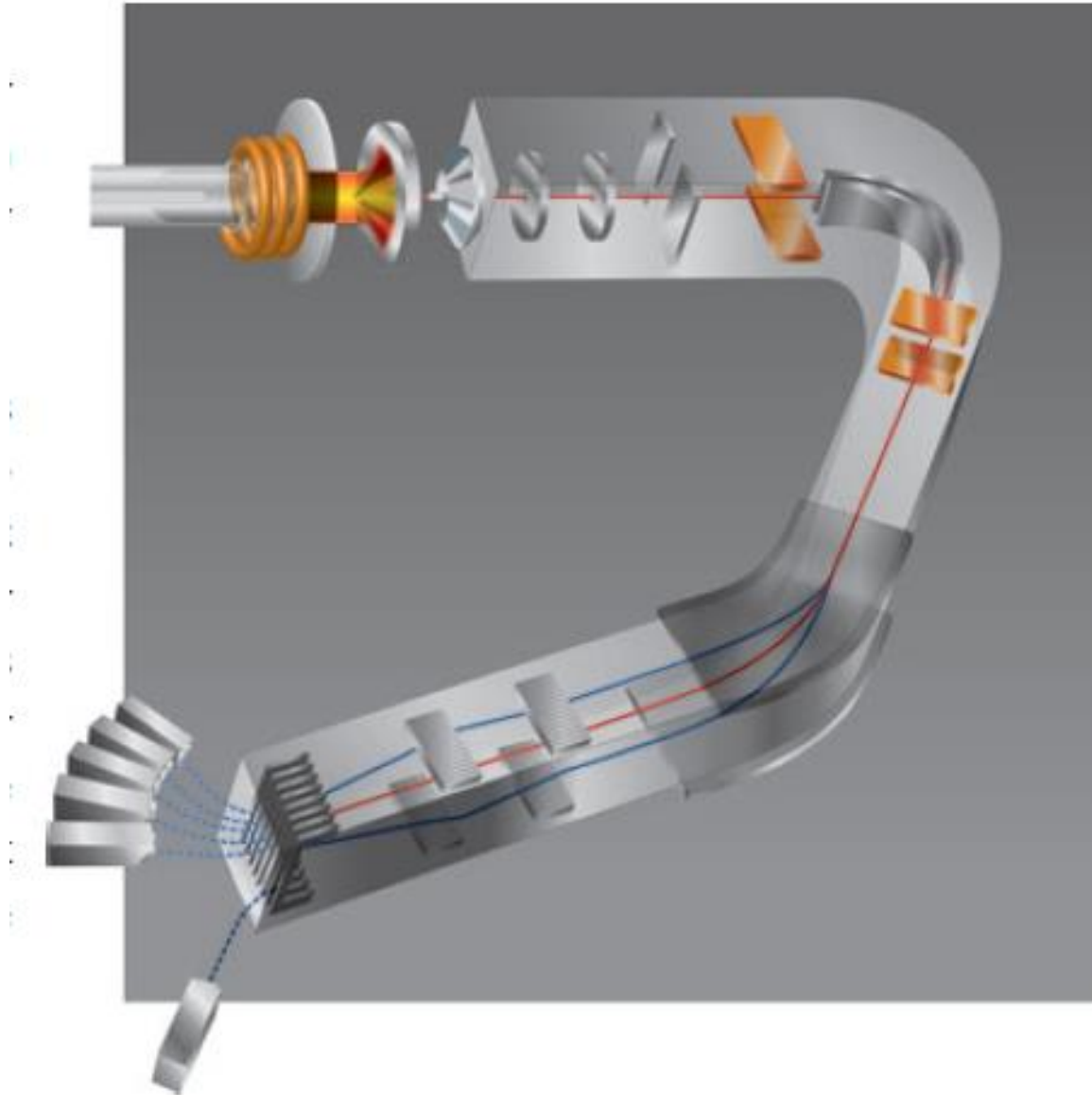
$$F_c = mv^2 / r = ezE$$
$$2zeV / r = ezE$$
$$r = 2V / E$$

# Double-Focusing Mass Spectrometer

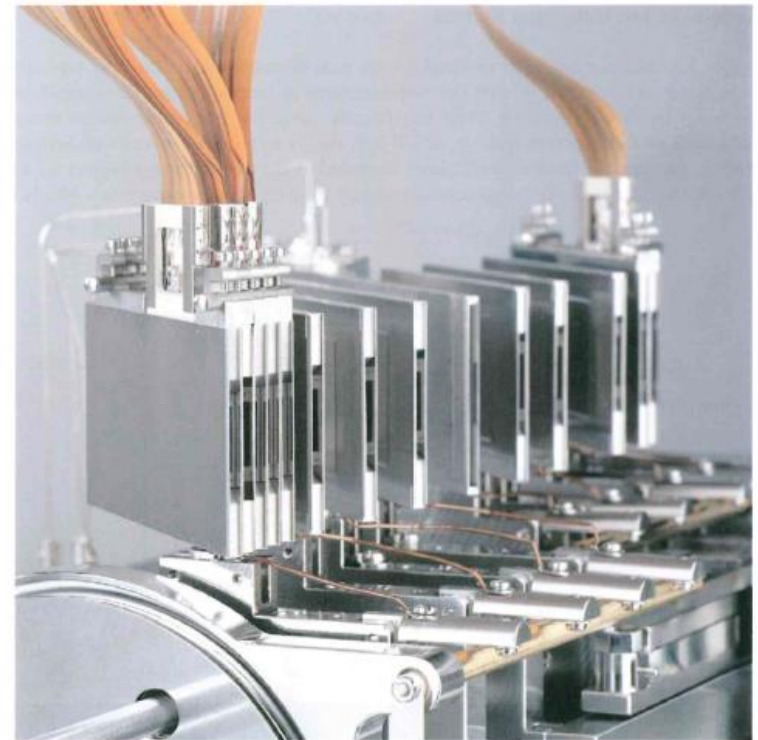
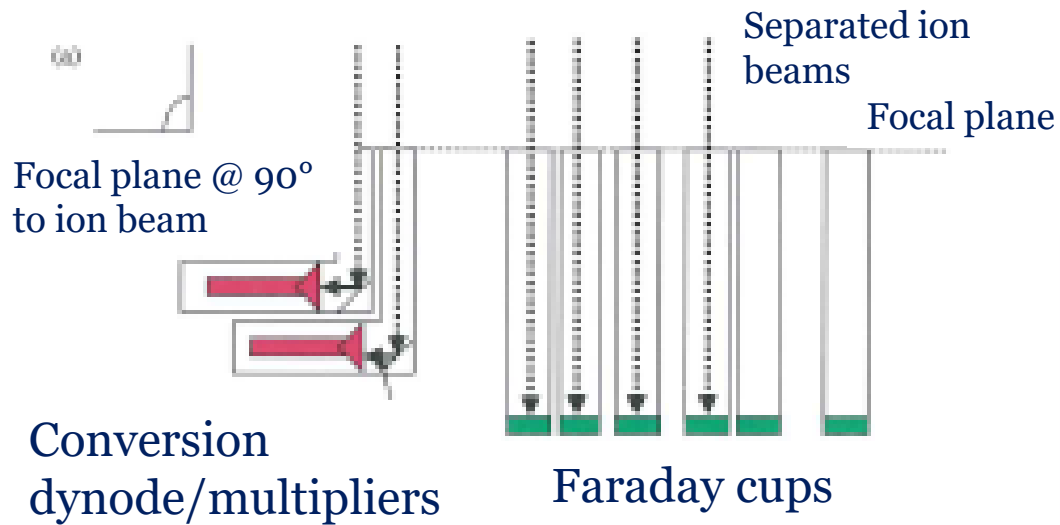




# Multicollector ICP-MS



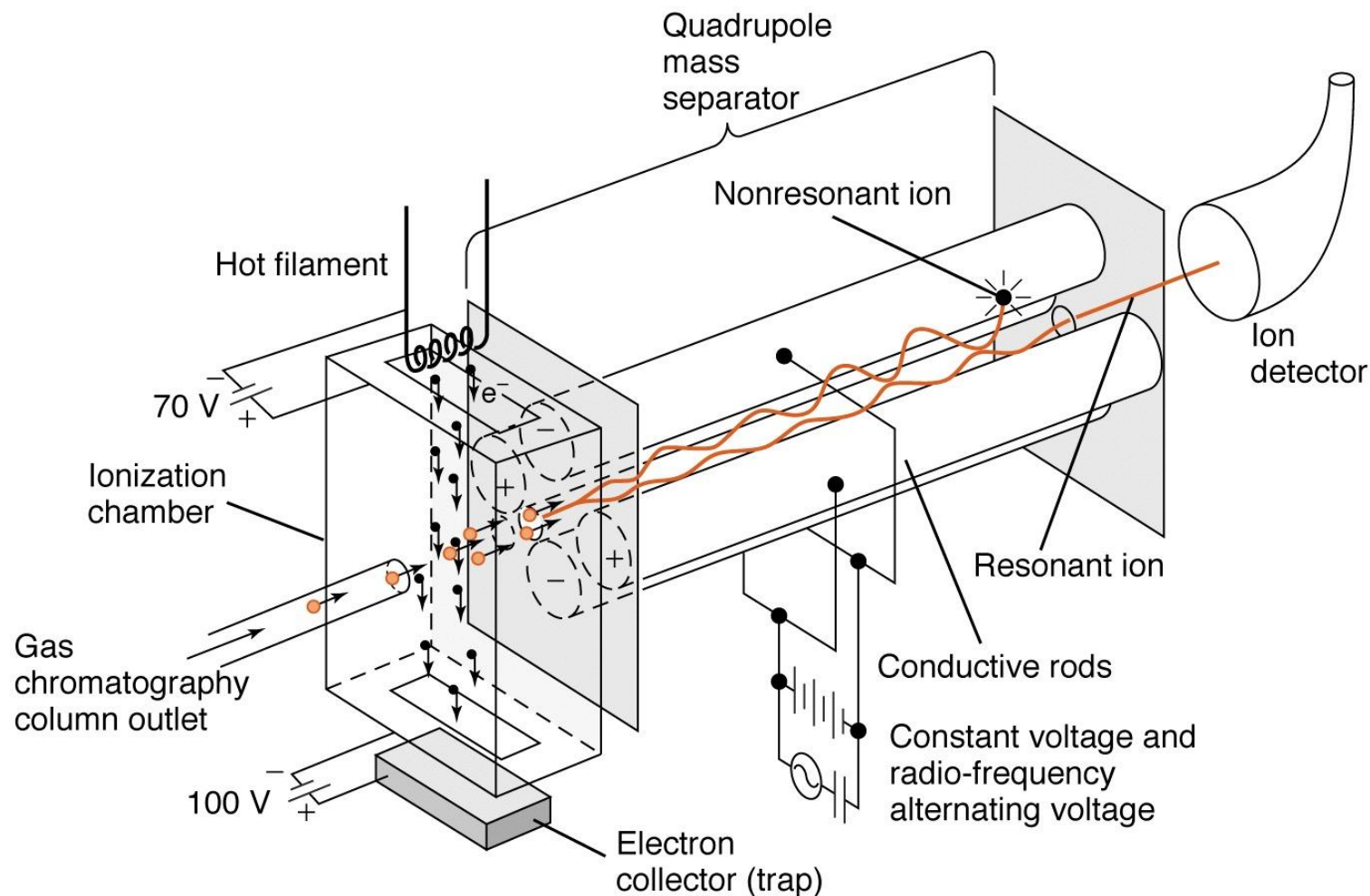
# Faraday Plate Array



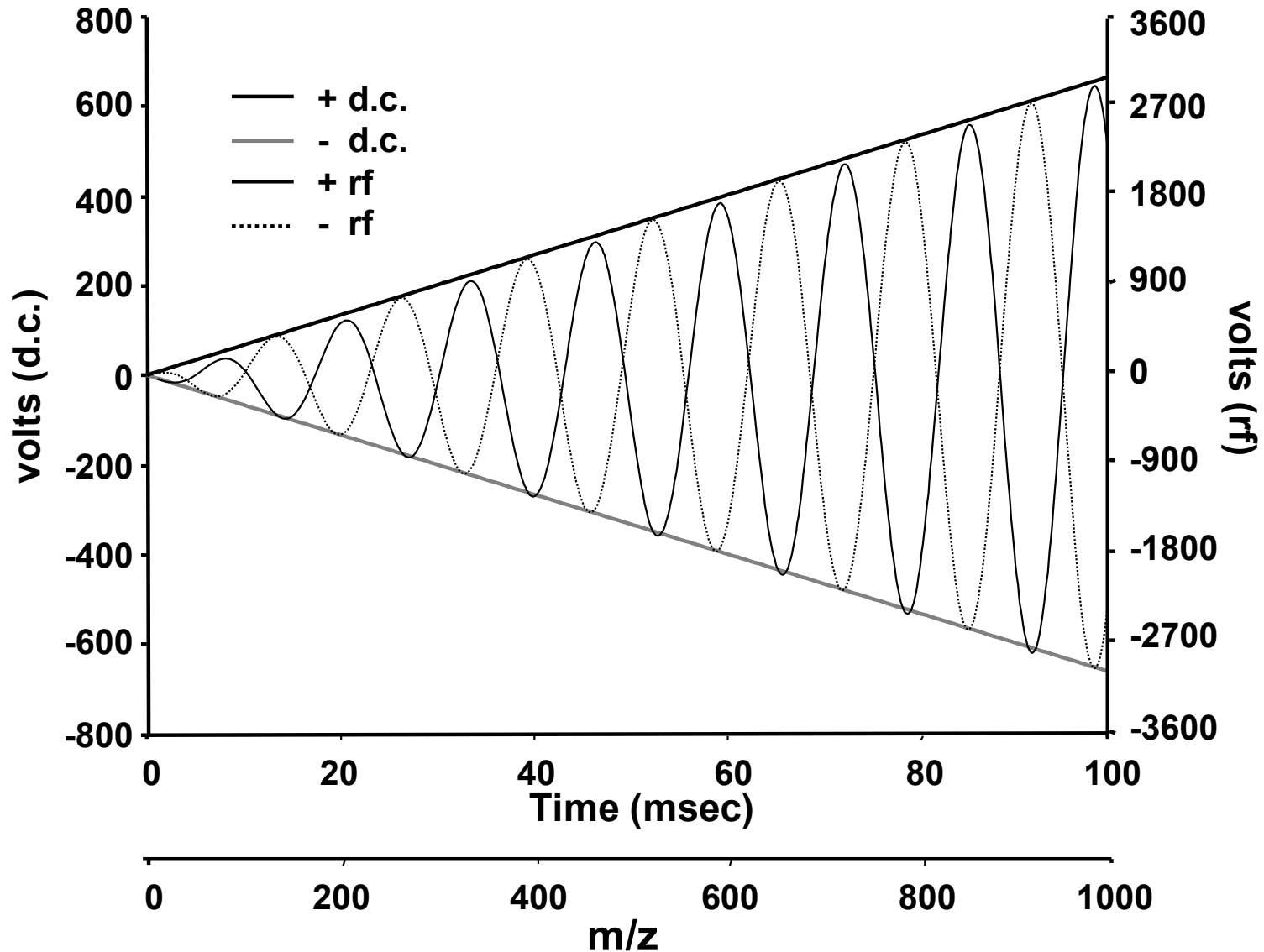
**Figure 4.8** Multiple ion collector array from MC-ICP-MS NEPTUNE and MC-TIMS TRITON (Thermo Fisher Scientific, Bremen). Miniaturized ion counters identical in size to Faraday detectors are mounted in the high mass range to detect, e.g., low-abundance uranium isotopes. (Reproduced by permission of Thermo Fisher Scientific, Bremen.)



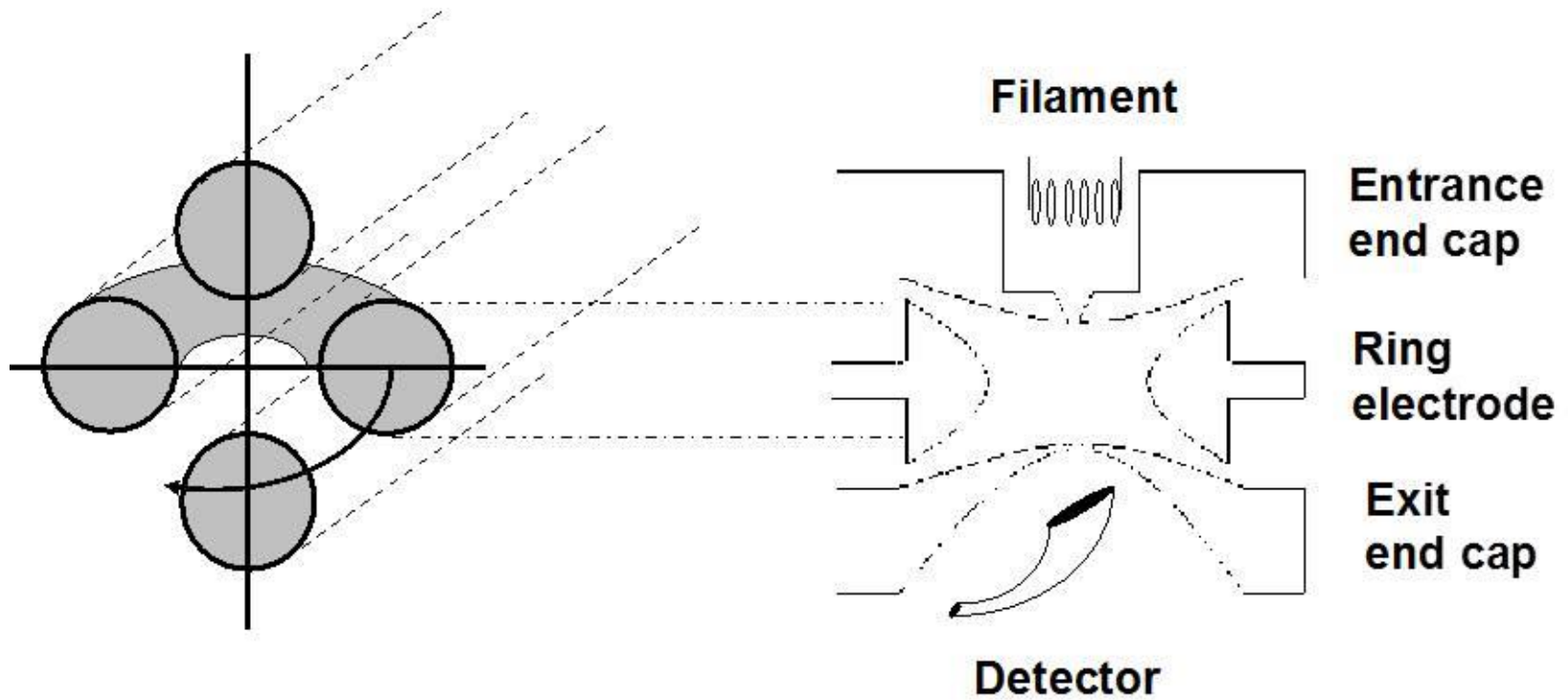
# Quadrupole Mass Filter



# QMF Scan Functions



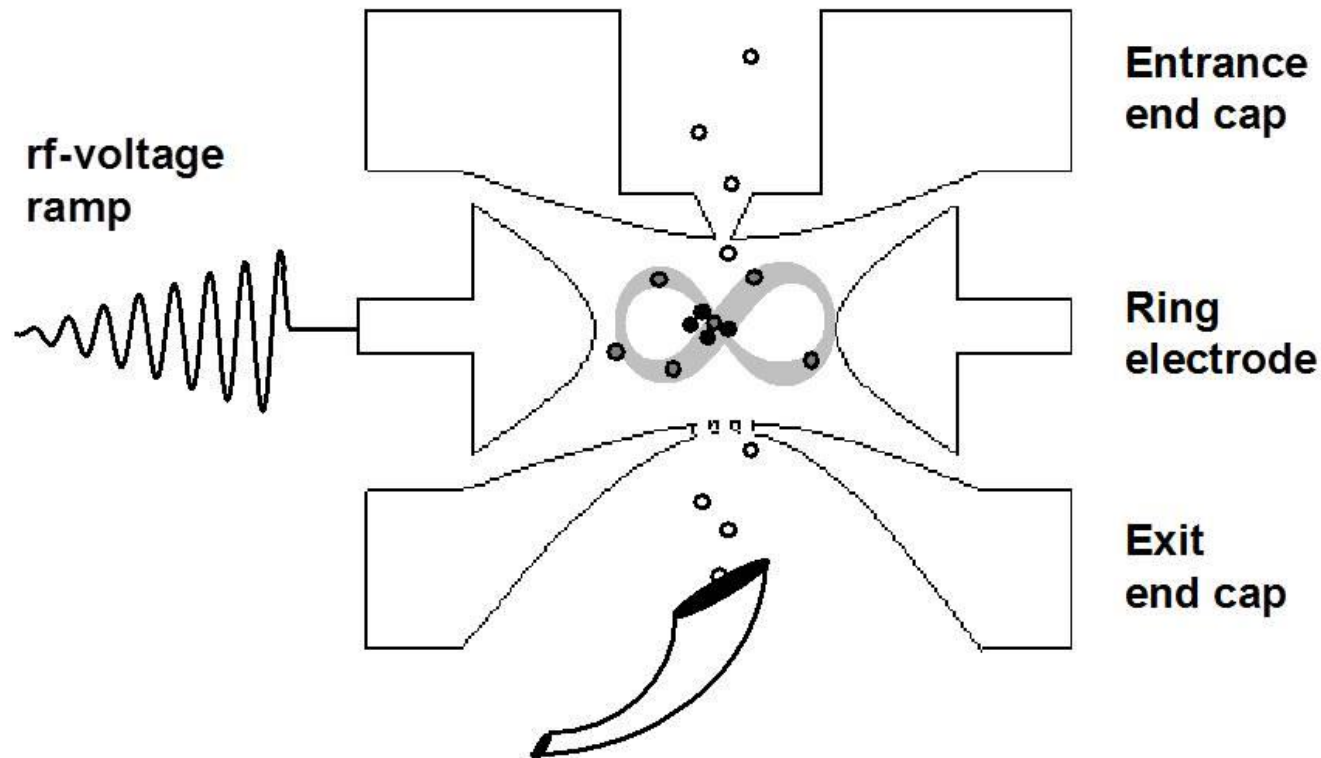
# Quadrupole Ion Trap



# Quadrupole Ion Trap

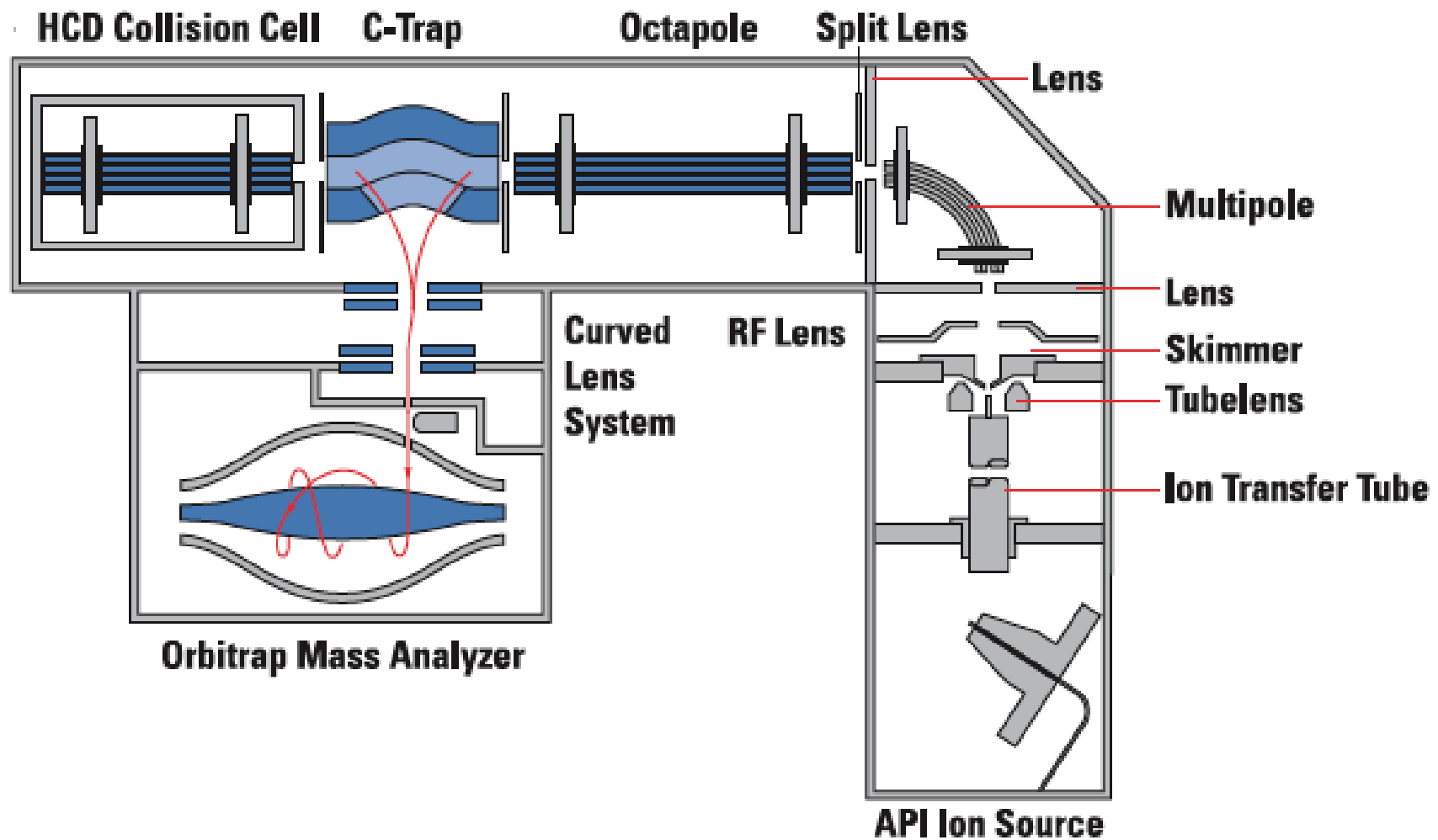


# Quadrupole Ion Trap





# Orbitrap Mass Analyzer



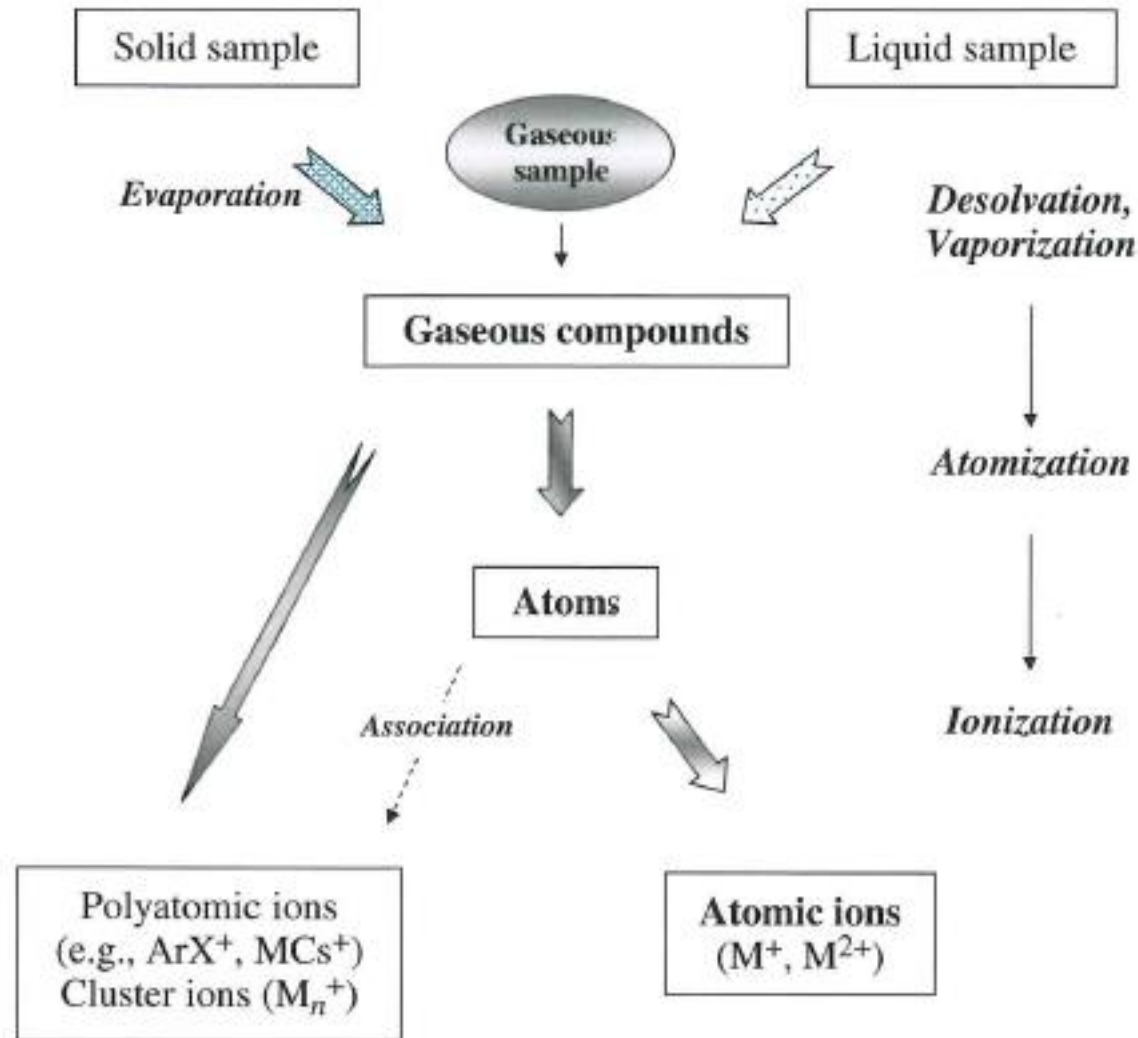
# In Summary . . . .

<b>Analyzer</b>	<b>Acronym</b>	<b>Pressure (Torr)</b>	<b>Mass range (Da)</b>	<b>Mass resolution (m/<math>\Delta</math>m)</b>	<b>Scan rate (Da/sec)</b>
<b>Magnetic sector</b>	<b>B</b>	<b>&lt;10<sup>-8</sup></b>	<b>10,000</b>	<b>5,000</b>	<b>500</b>
<b>Electrostatic sector</b>	<b>ESA, E</b>	<b>&lt;10<sup>-8</sup></b>	<b>NA</b>	<b>NA</b>	<b>NA</b>
<b>Double focusing</b>	<b>E/B, B/E</b>	<b>&lt;10<sup>-8</sup></b>	<b>10,000</b>	<b>40,000</b>	<b>500</b>
<b>Time of flight</b>	<b>ToF</b>	<b>&lt;10<sup>-7</sup></b>	<b>&gt;100,000</b>	<b>&gt;5,000</b>	<b>10,000 Hz</b>
<b>Quadrupole</b>	<b>QMS, Q</b>	<b>&lt;10<sup>-6</sup></b>	<b>2,000</b>	<b>unit</b>	<b>2,000</b>
<b>Quadrupole ion trap</b>	<b>ITMS</b>	<b>&lt;10<sup>-3</sup></b>	<b>600</b>	<b>unit-10,000</b>	<b>2,000</b>
<b>Orbitrap</b>		<b>&lt;10<sup>-9</sup></b>	<b>2,000</b>	<b>60-100,000</b>	<b>Up to 1 kHz</b>

# Ion sources . . . .

- What is the physical form of the sample?
  - Solid
  - Liquid
  - Gas
- What type of information do you want?
  - Qualitative
  - Quantitative
  - Isotopic
  - Molecular
- What analytical figures of merit?
  - Precision
  - Accuracy
  - Limits of detection
- How much sample prep are you willing to do?
- Time, cost, portability . . . ?

# The cumulative process . . . .



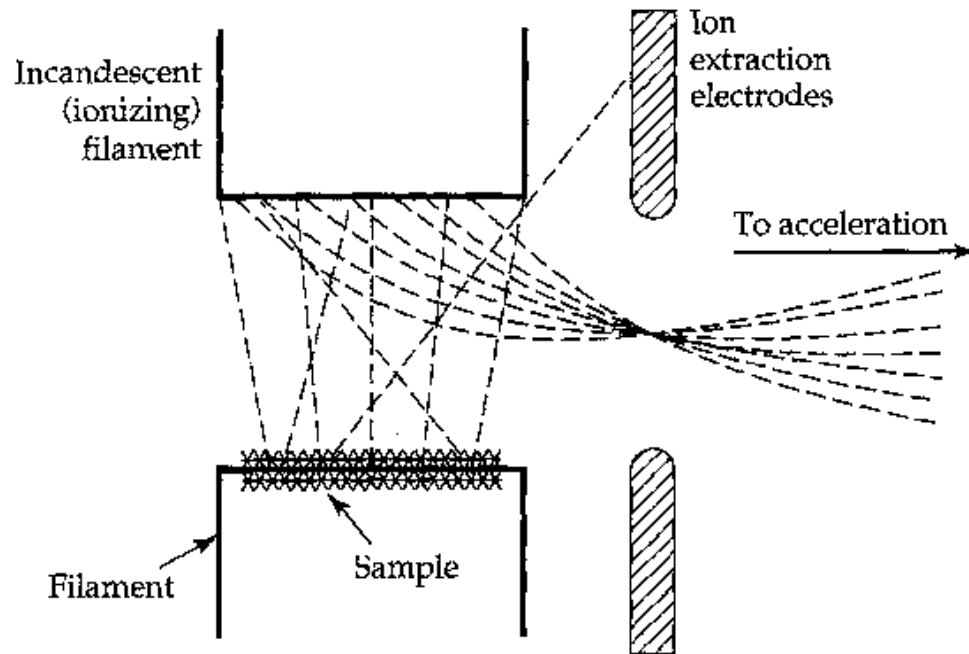
# Elemental/Isotopic Ionization Sources

- Thermal ionization (TIMS)
- Secondary ion mass spectrometry (SIMS)
- Inductively-coupled plasma (ICP-MS)
- Glow discharge (GDMS)
- Resonance ionization (RIMS)

# Thermal Ionization Mass Spectrometry

- Thermal release of solid analyte (residues, solids, analytes in polymer matrices) from metal filament
- Ionization via electron extraction/attachment at filament surface or in the gas phase with secondary filament
- Ions emitted with low KE spread
- **Very** element-specific (poor multi-element)
- Stable operation (great for IR measurements)
- Limited concentration sensitivity
- Sample prep comparable radiochem (or worse)

# TIMS



◀ FIGURE 12.25  
Diagram of a thermal-ionization source.

The sample is evaporated off the hot wire and some of the material becomes ionized at the incandescent filament. Ions of one charge are extracted into the acceleration region and then into the mass analyzer.

$$\text{Ionization efficiency} = E^+ = N^+/N_0 = A \exp(\Phi - IE/kT)$$

where  $\Phi$  is the work function of the filament and  $I$  is the IE of the analyte

# TIMS

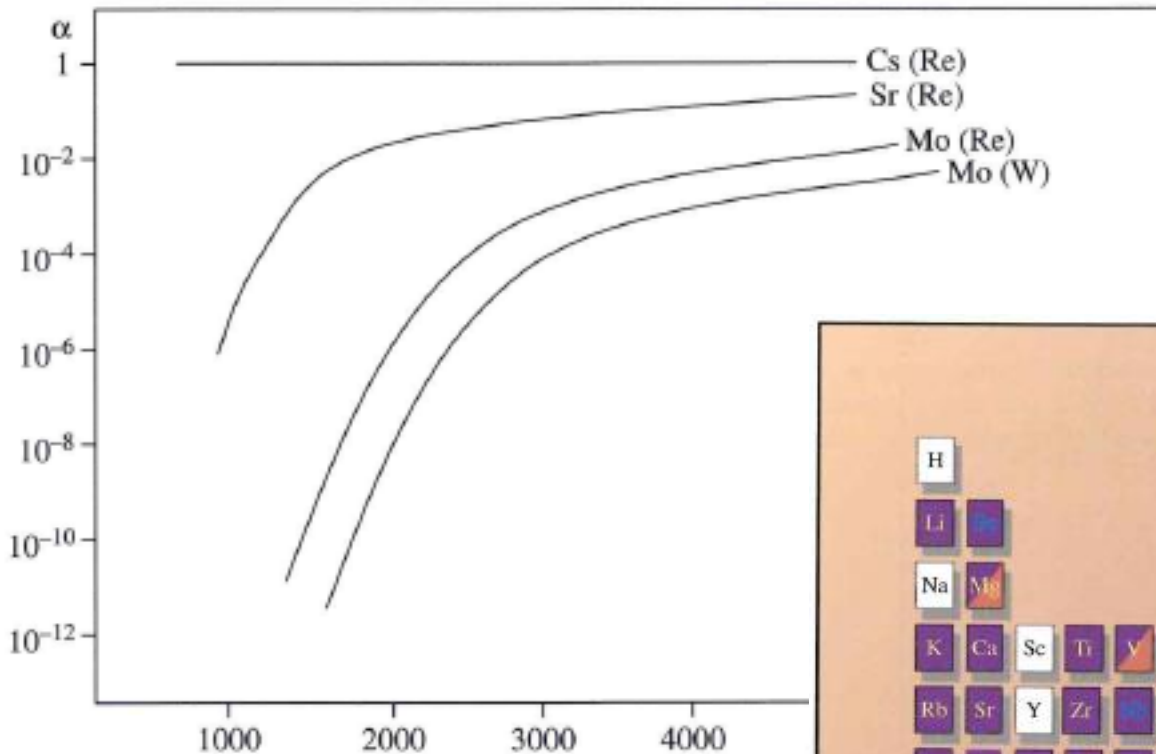
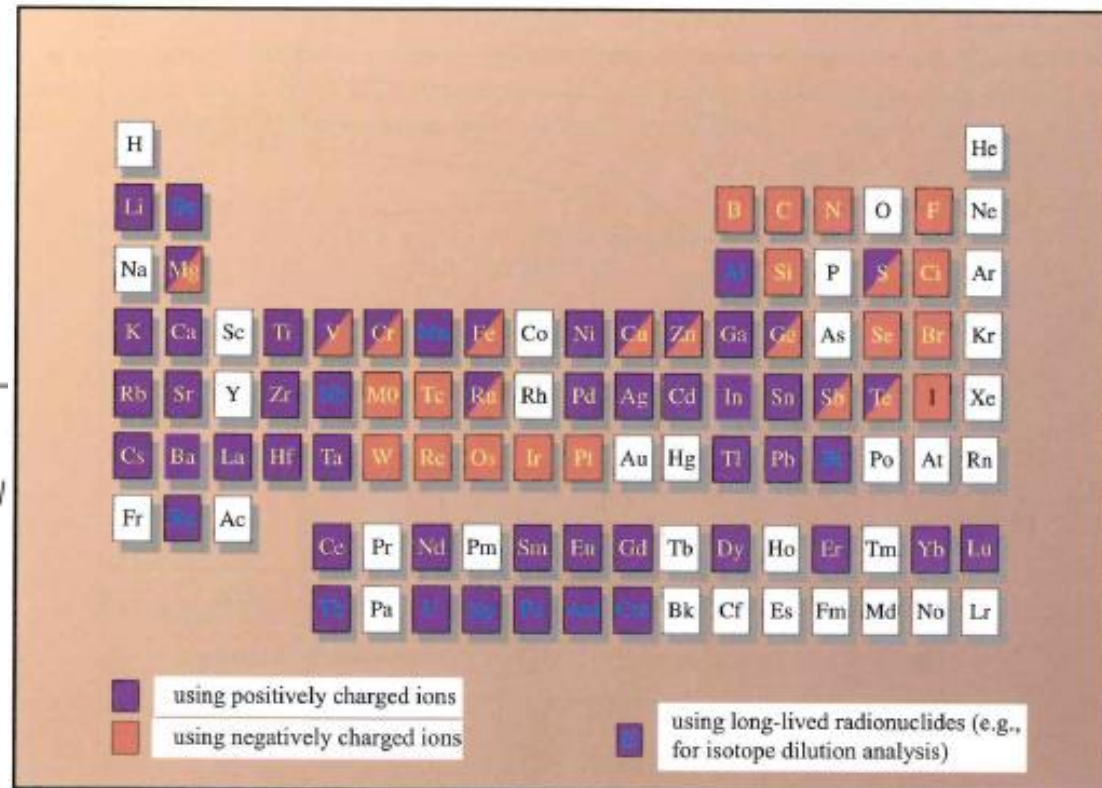


Figure 2.27 Typical ionization curves in thermal

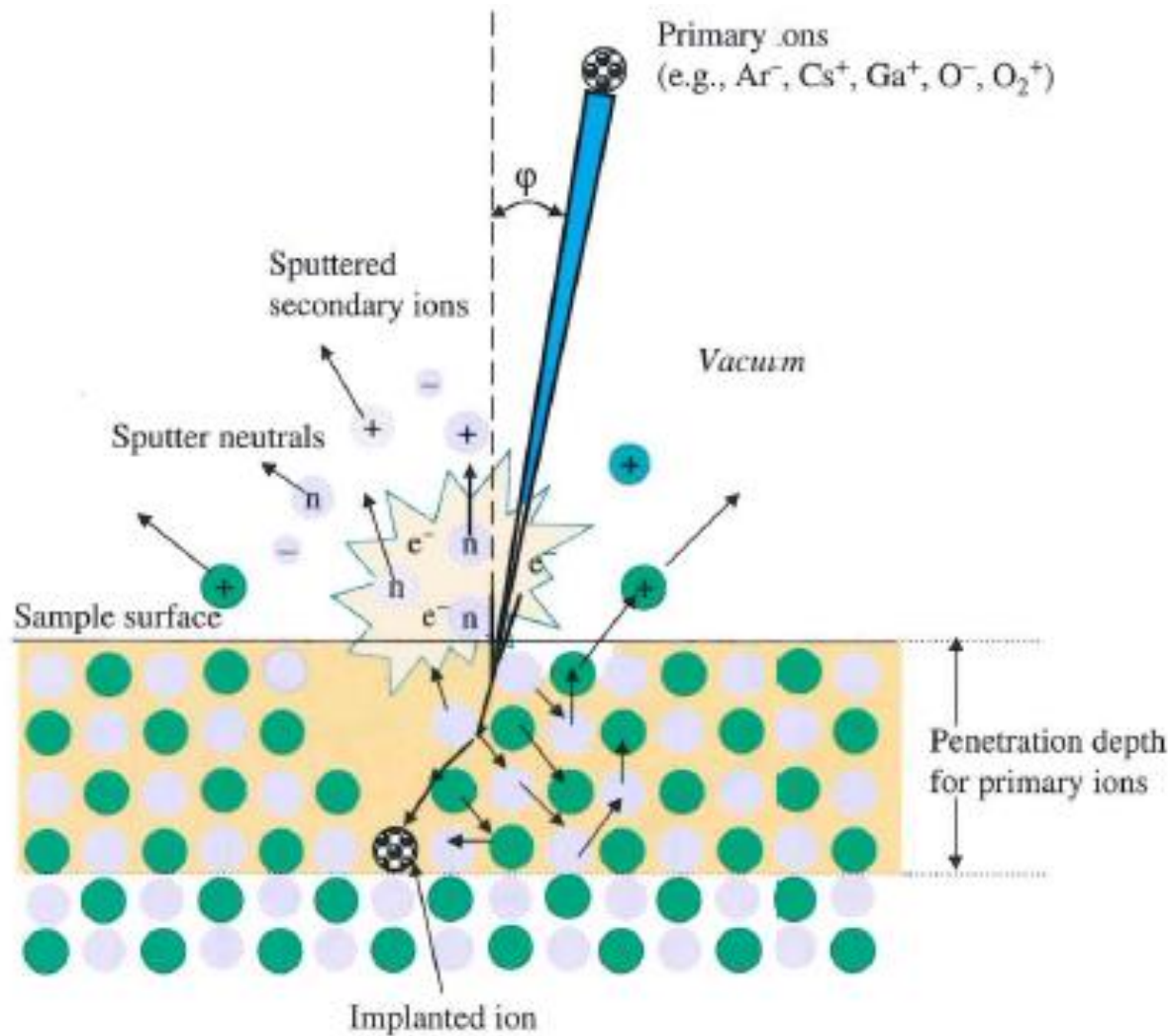




# Secondary Ion Mass Spectrometry

- Direct analysis of solids of various form
- High energy ion beams “sputter” neutrals, ions, electrons, and clusters from surface
- High degree ( $<1 \mu\text{m}$ ) of lateral and depth resolution
- Operation in both positive and negative ion modes
- Exceedingly high mass sensitivity
- Very low sample throughput and exceedingly wide of elemental response factors

# SIMS



## SIMS

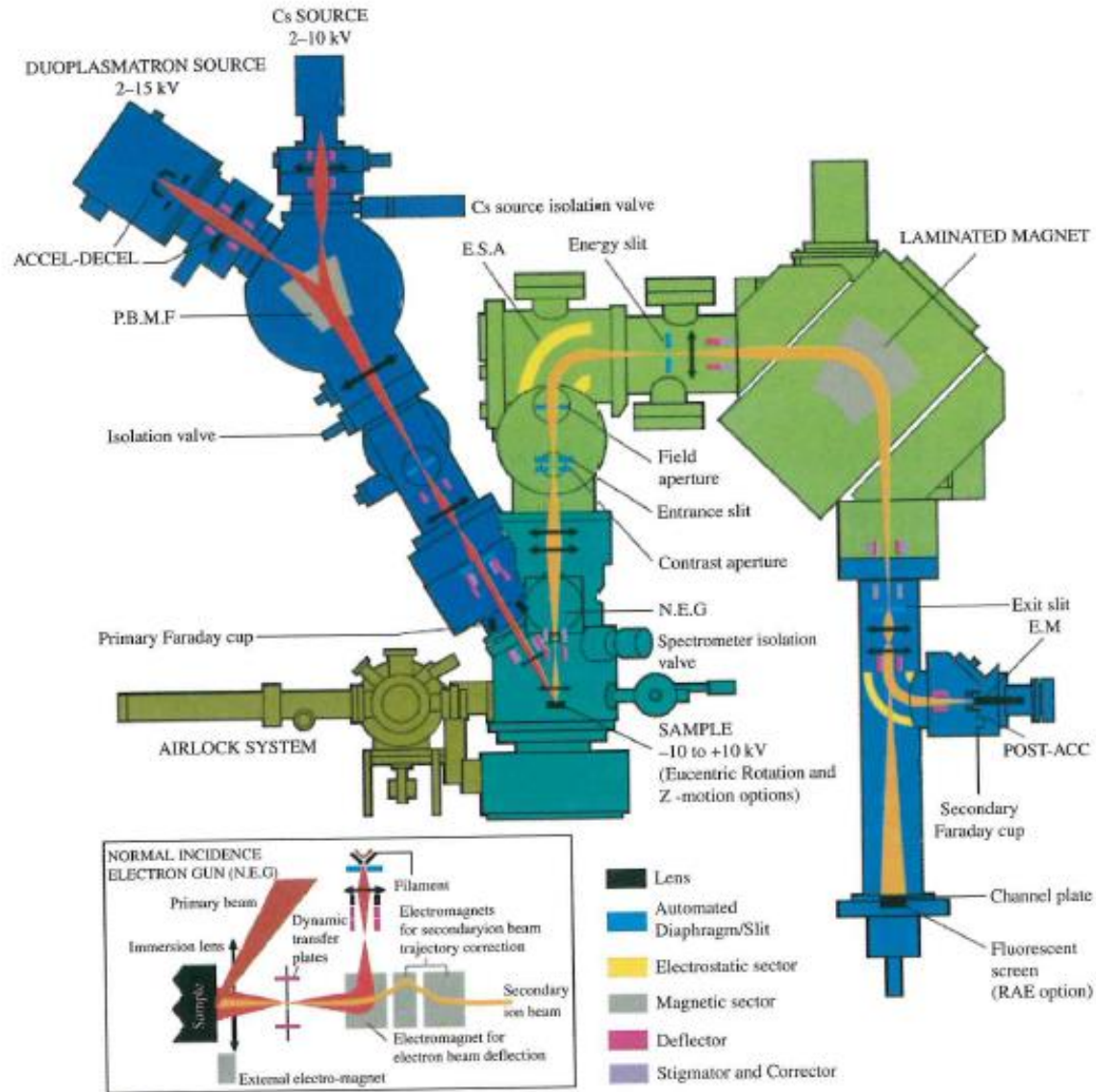
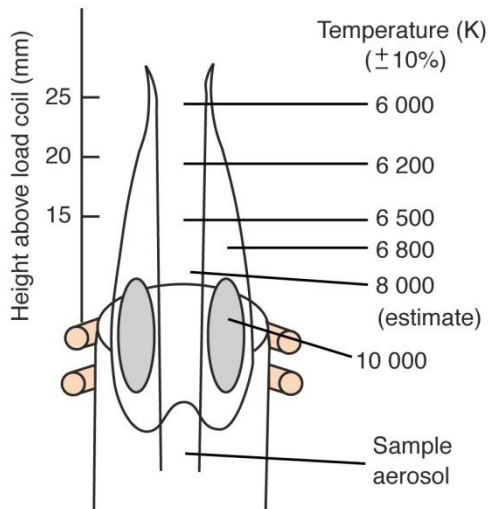
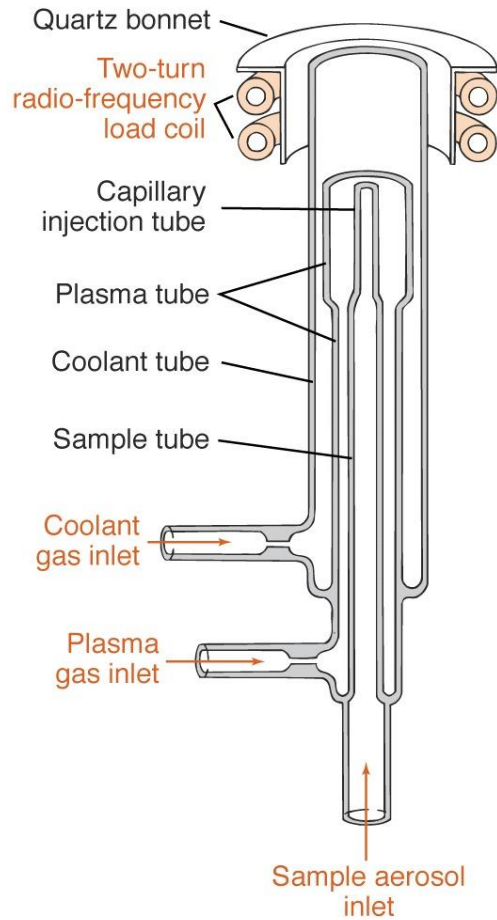


Figure 5.31 Instrumental arrangement of secondary ion mass spectrometer, CAMECA IMS 7f (Reproduced by permission of CAMECA, [www.cameca.com](http://www.cameca.com).)

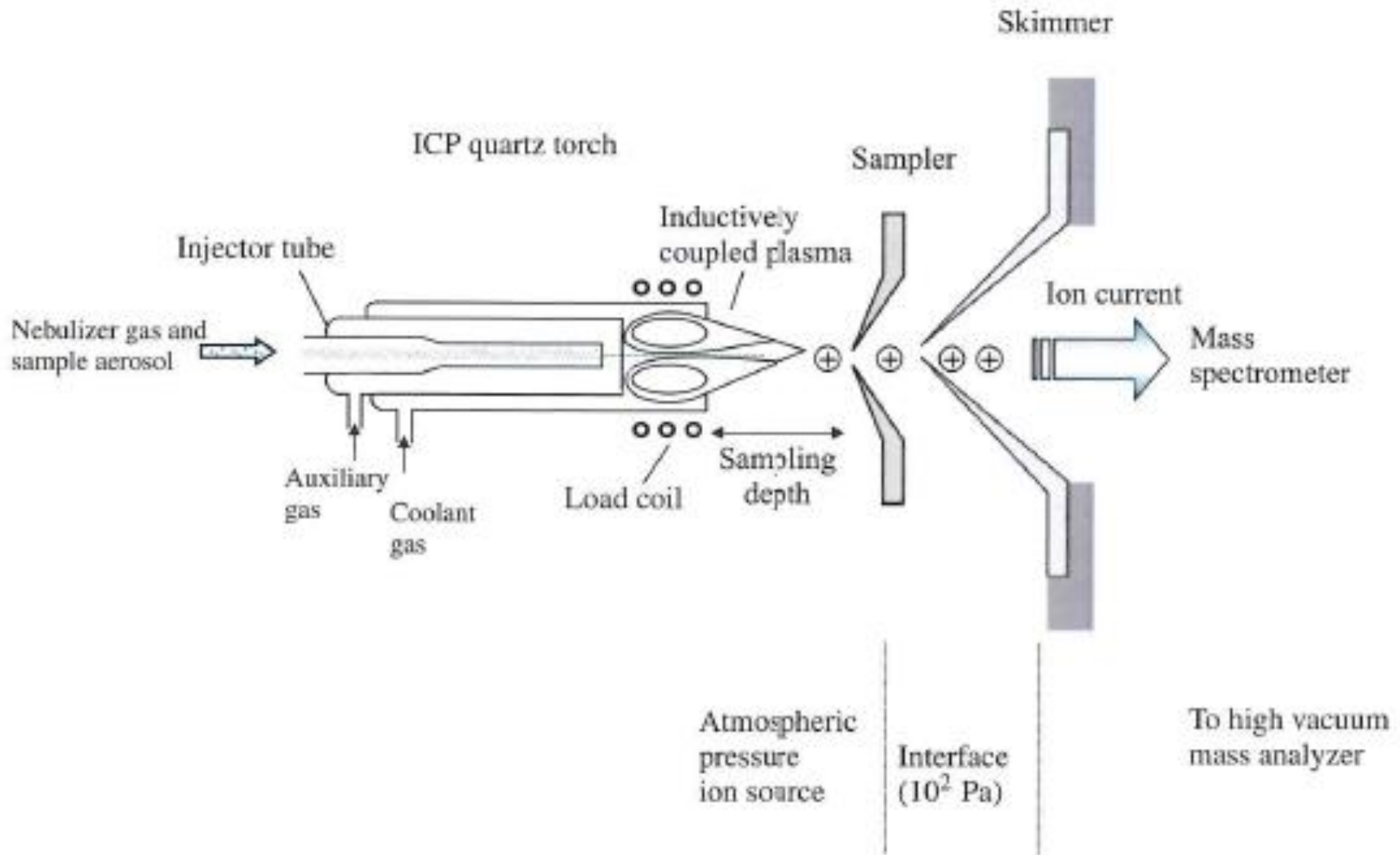
# Inductively-Coupled Plasma Mass Spectrometry

- Most widely applied elemental analysis ionization source
- High (kinetic) temperature plasma affects efficient desolvation/vaporization/ionization
- Very uniform elemental responses, with very low LODs
- Very high operational overhead (1-2 kW, 16 L min<sup>-1</sup> support gas, extreme vacuum challenges)
- Multitude of different sample introduction approaches; thus a diversity of sample forms
- Diversity of mass analyzers based on analytical challenges

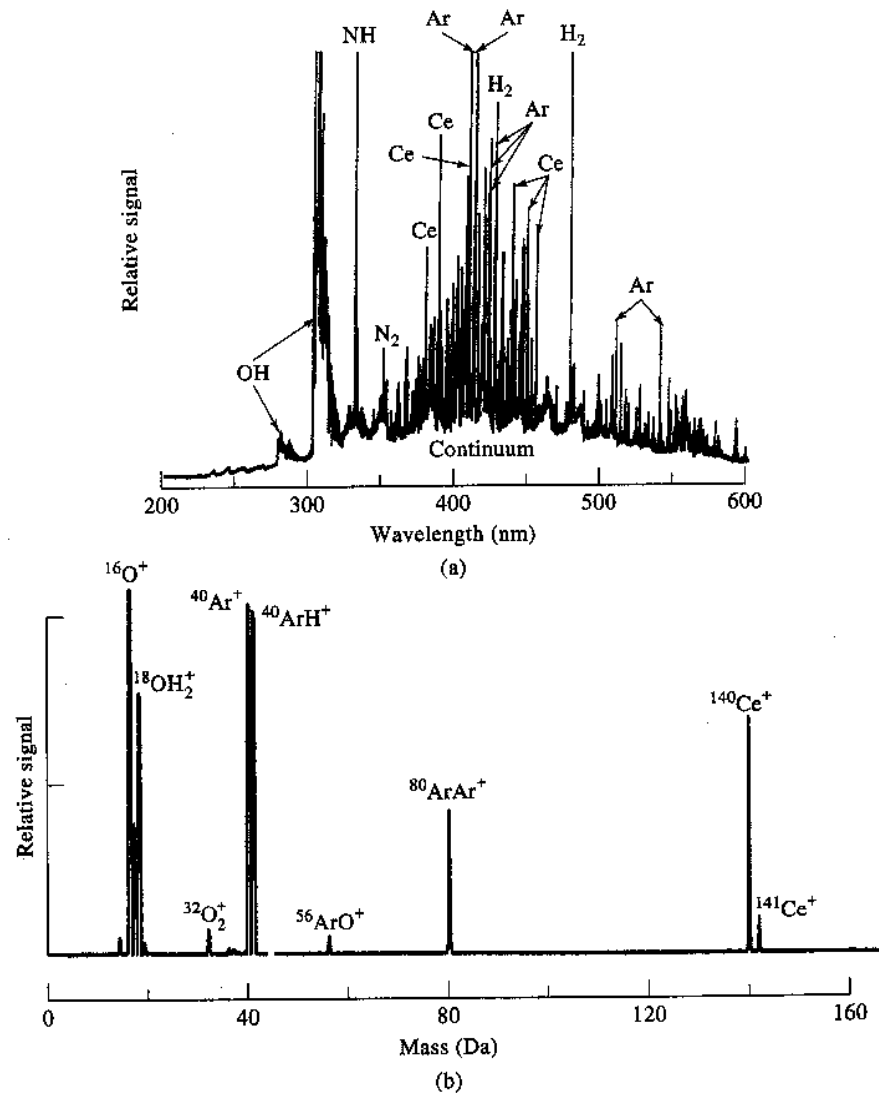
# ICP-MS



# ICP-MS

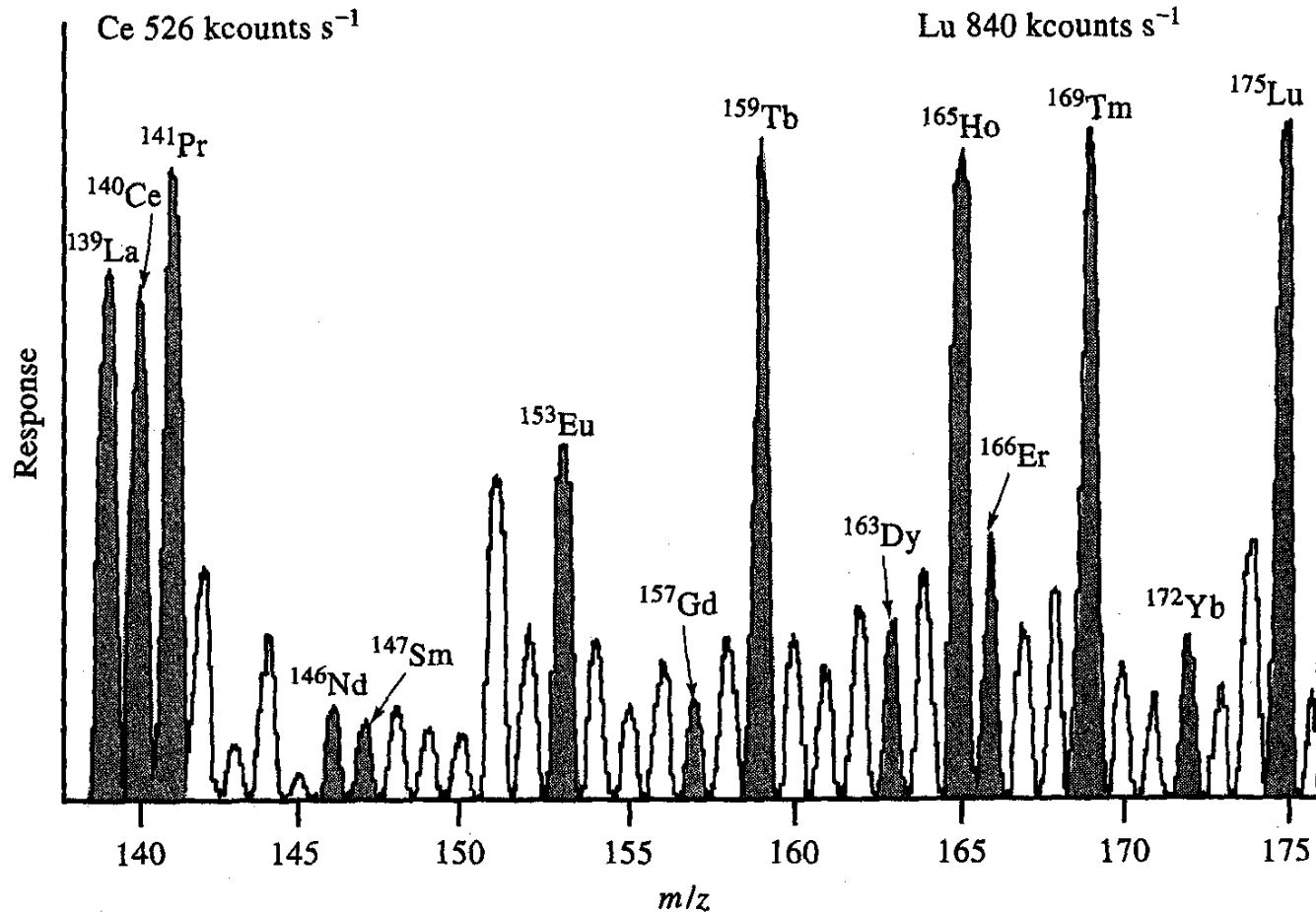


# ICP-MS



**Figure 11-12** Comparison of (a) optical ICP spectrum for 100 ppm cerium and (b) mass ICP spectrum for 10 ppm cerium.

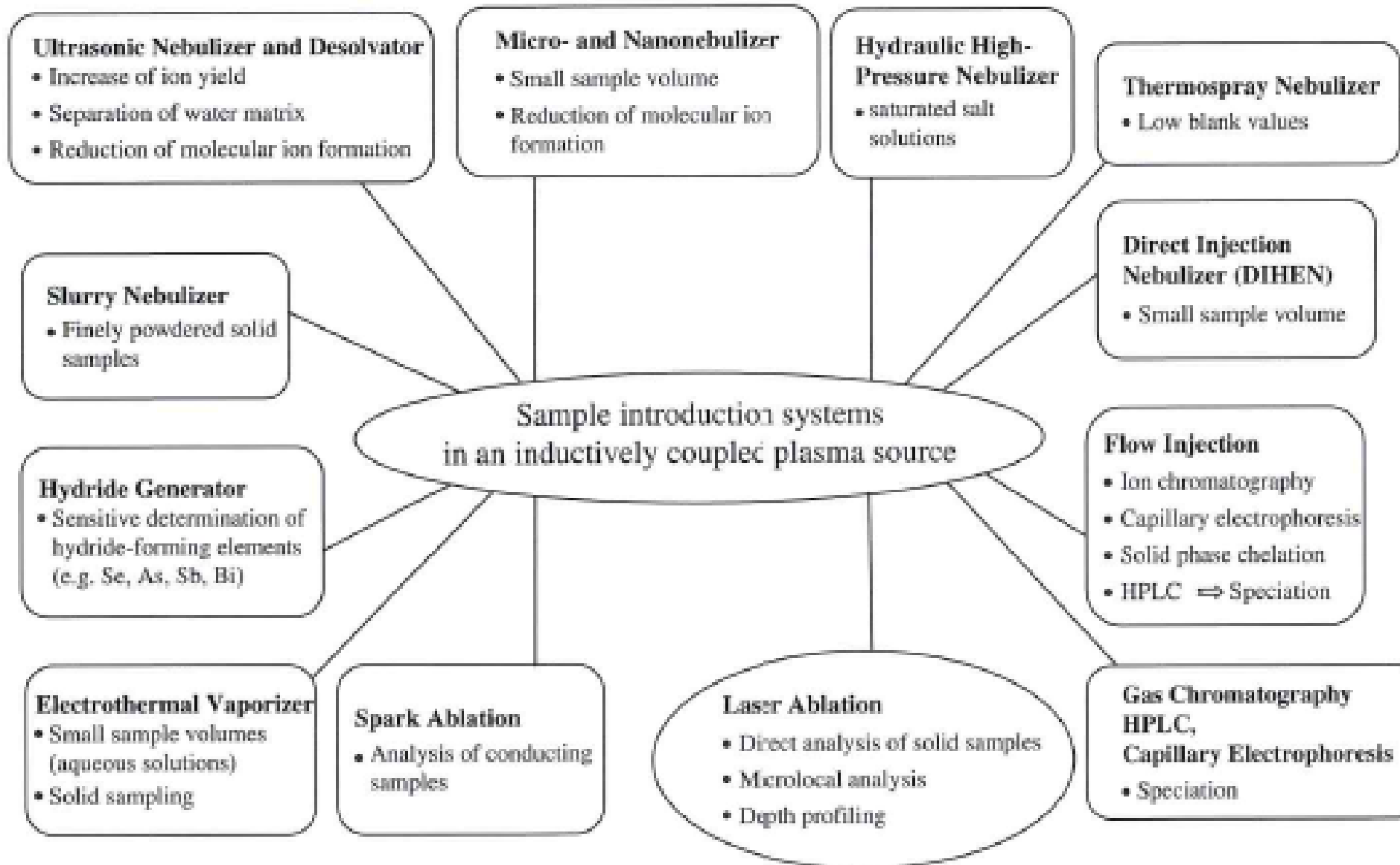
# ICP-MS



**Figure 11-13** ICPMS spectrum for the rare earth elements. Solutions contain 1  $\mu\text{g/mL}$  of each element. (From K. E. Jarvis, *J. Anal. Atom. Spectrom.*, 1989, 4, 563. With permission.)



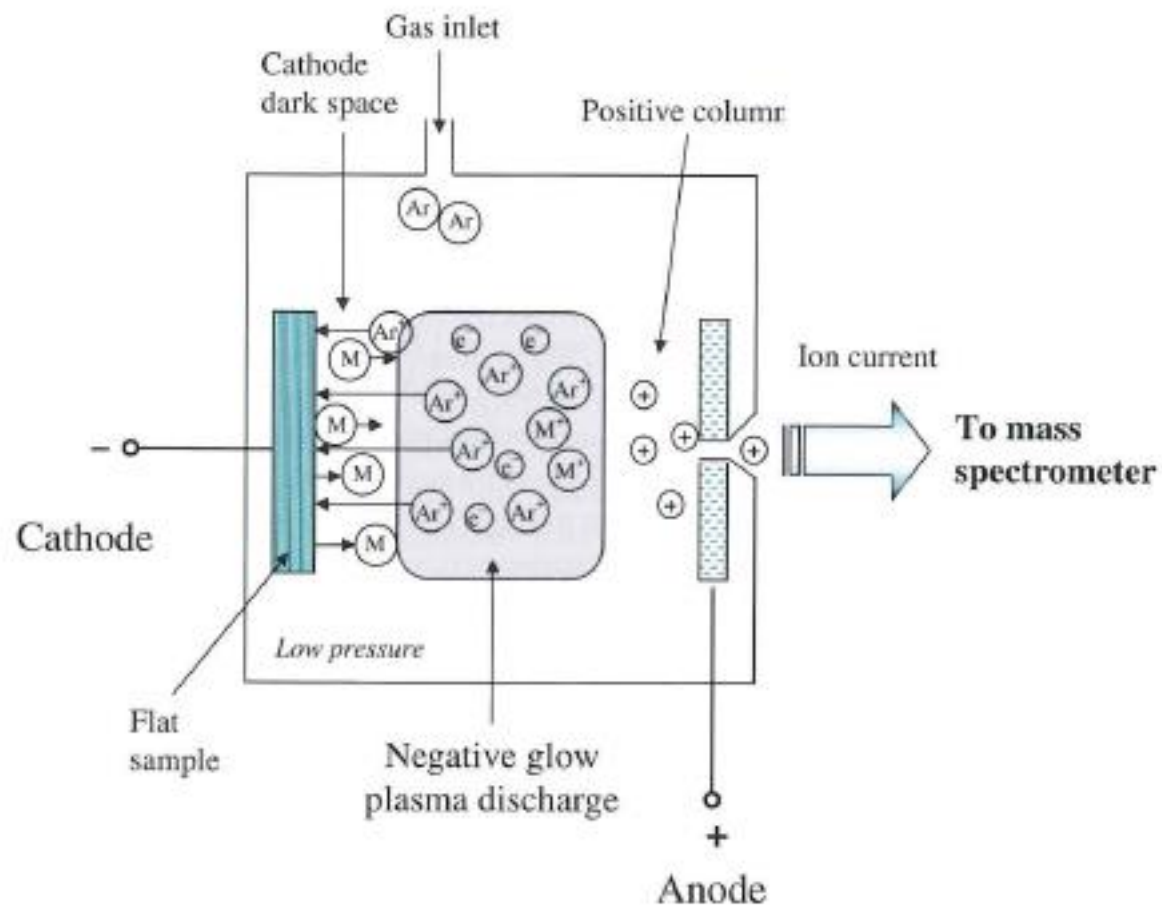
# ICP-MS



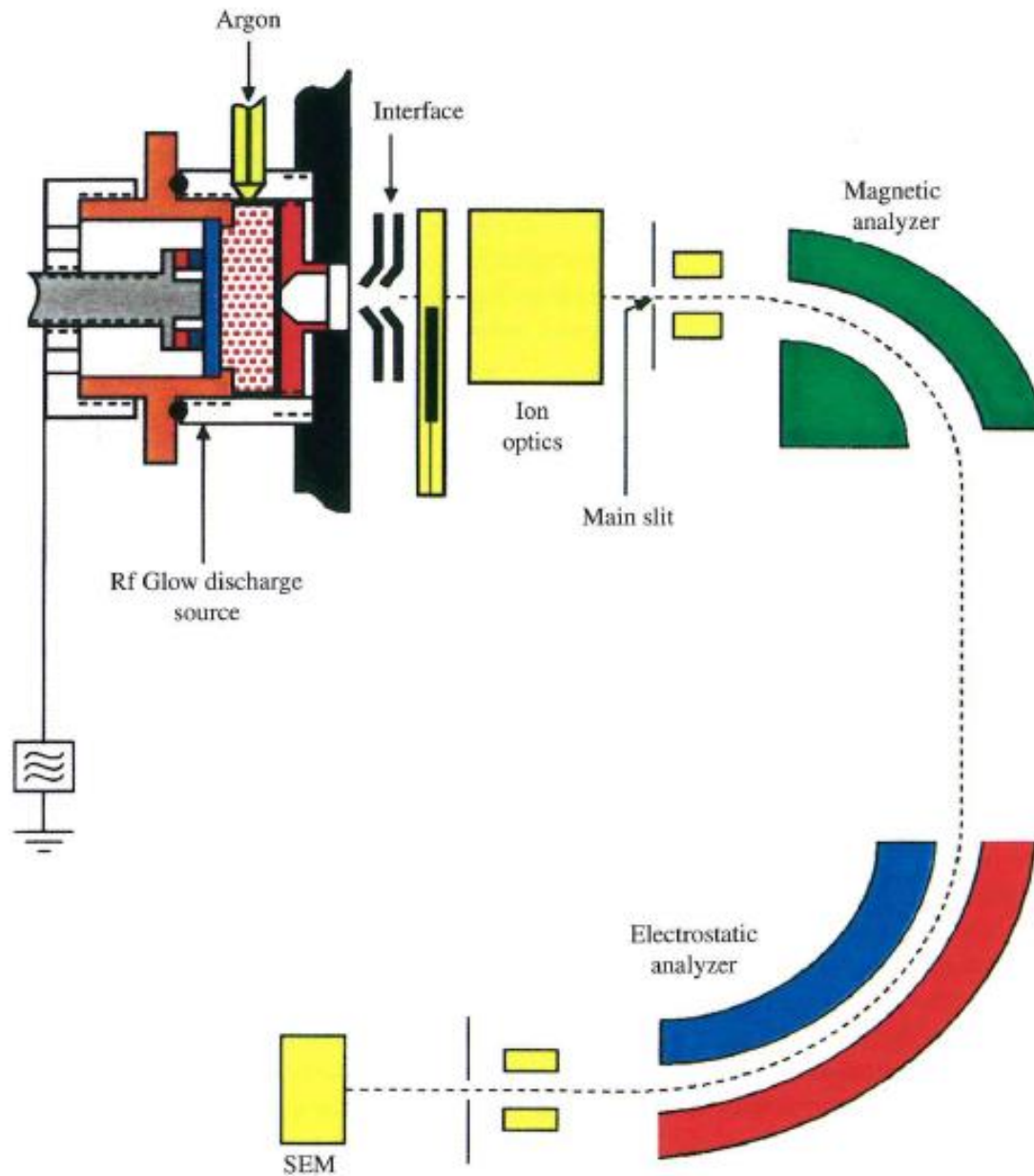
# Glow Discharge Mass Spectrometry

- Direct solids elemental analysis
- Conductive samples via d.c. powering, insulators via rf
- Extremely stable operation
- Very uniform elemental responses
- Extremely high elemental sensitivity (sub-ppm in solids)
- Depth profiling with ~10 nm resolution
- Low sample throughput

# GDMS



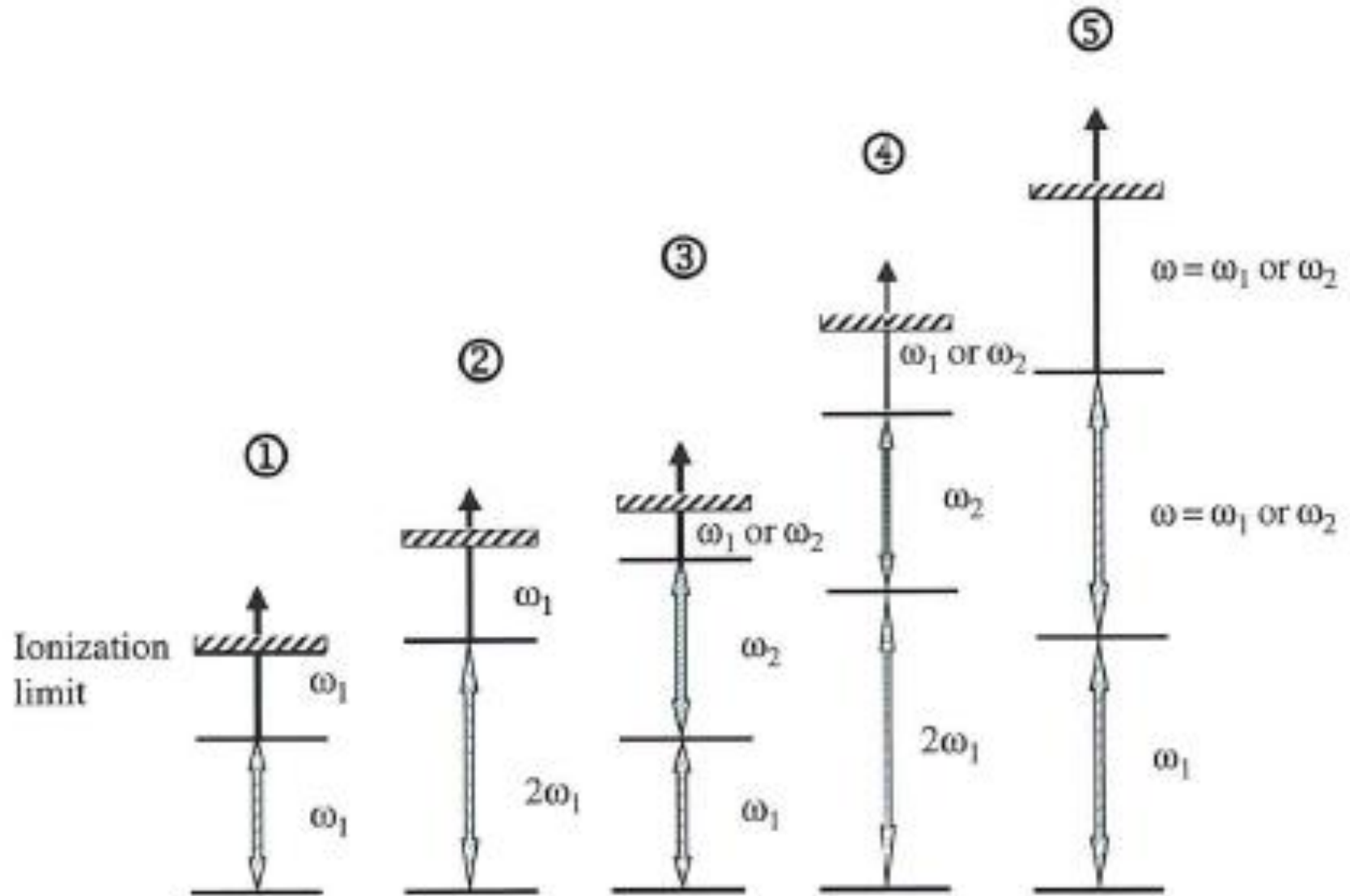
# GDMS

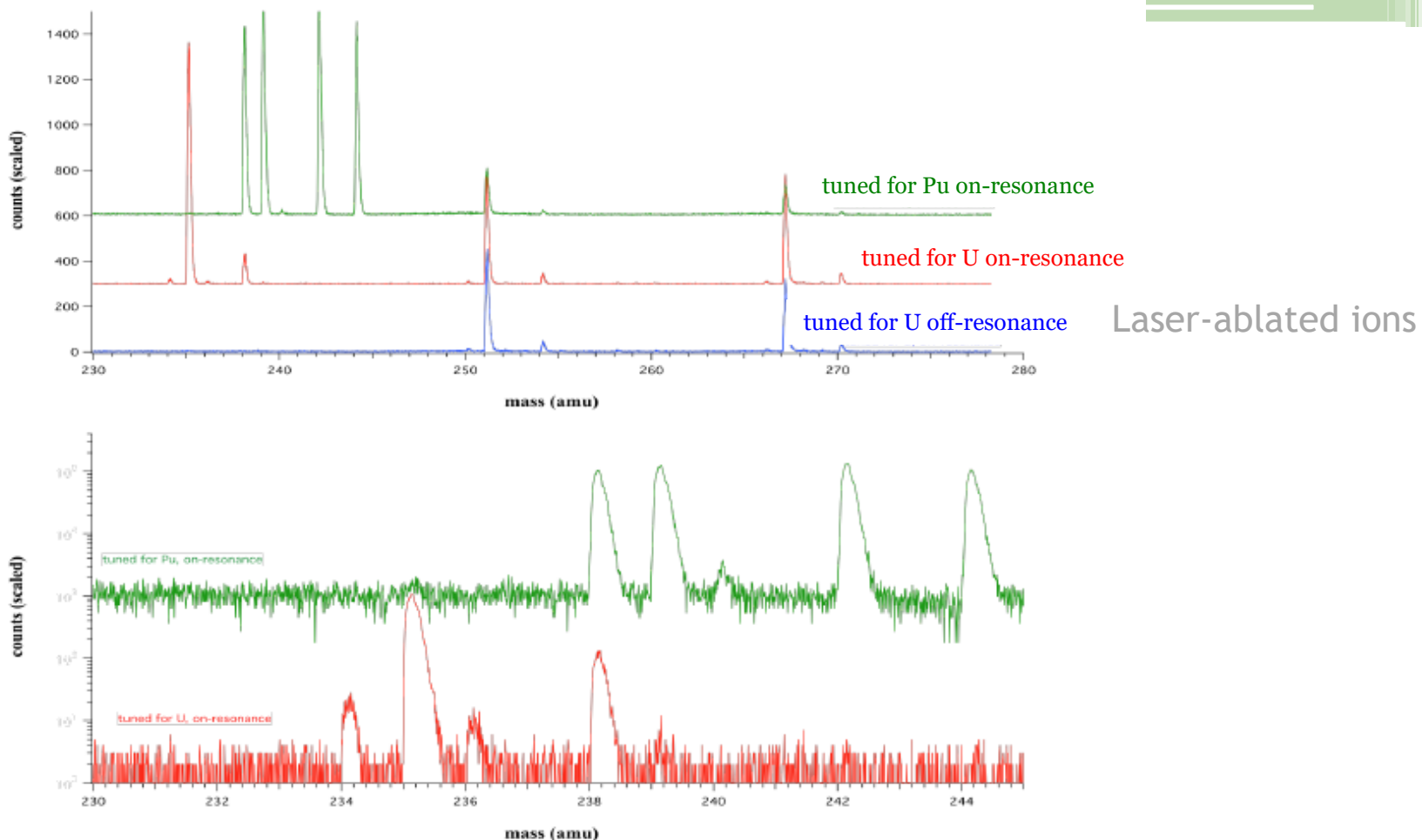


# Resonance Ionization Mass Spectrometry

- Elemental specificity based on electronic, optical transitions
- Elemental selectivity can be fine-tuned to the isotopic level
- Means of isolating elements that have isobaric interferences
- Imparting mass resolution not provided by mass analyzer
- Extremely complex and expensive instrumentation
- Requires means of converting solid samples into gaseous atoms

## RIMS





**Fig 3** 3-color Pu resonant and non-resonant ionization spectra from a titanium stub electrodeposited with a 4-Pu-isotope and enriched U solution. The panel shows (green, top spectrum) the signal when tuned to Pu, the second (red) spectrum shows the signal using lasers tuned to U, and the third (blue) spectrum shows the background, when the first resonance laser is detuned 200 pm. The bottom figure shows the resonant Pu and U signals on a log scale. No significant off-resonance or laser-induced backgrounds were observed. All data are scaled to 25,000 laser shots and are offset arbitrarily in the vertical axis for clarity.

# In Summary . . . .

<b>Ion Source</b>	<b>Acronym</b>	<b>Sample forms</b>	<b>Sample introduction</b>	<b>Sensitivity</b>	<b>Spatial resolution</b>
<b>Thermal ionization</b>	<b>TIMS</b>	<b>liquid (gas)</b>	<b>filament vaporization</b>	<b>pg-ng</b>	<b>NA</b>
<b>Secondary ion</b>	<b>SIMS</b>	<b>solid</b>	<b>sputtering</b>	<b>0.1 ppb-ppm</b>	<b>&lt;0.2 <math>\mu\text{m}</math> (lat), 1-5 nm (depth)</b>
<b>Inductively-coupled plasma</b>	<b>ICP-MS</b>	<b>solid, liquid (gas)</b>	<b>nebulization, laser ablation, . .</b>	<b>pg-ng</b>	<b>1-5 <math>\mu\text{m}</math> using LA</b>
<b>Glow discharge</b>	<b>GDMS</b>	<b>solid (gas)</b>	<b>sputtering</b>	<b>0.1 ppb-ppm</b>	<b>1-5 nm (depth)</b>
<b>Resonance ionization</b>	<b>RIMS</b>	<b>solid (gas)</b>	<b>sputtering, laser ablation</b>		<b>1-5 <math>\mu\text{m}</math> w/LA SIMS-like with ions</b>



# Methods of quantification

- Calibration/response curves
- Relative sensitivity factors (RSFs)
- Isotope dilution mass spectrometry (IDMS)
  
- Speed and ease
- Susceptibility towards matrix effects
- Extent of prior knowledge about the sample
- Required accuracy
- Required precision

# Calibration curves

- Assumption of some well-behaved relationship between analyte response and concentration
- Some *a priori* knowledge of analyte concentration
- Matrix matching between sample and standards required
- Most efficient approach if performed in a multi-component mode
- Can be extended to the standard additions method as a means of correcting matrix effects

# Relative sensitivity factors (RSFs)

- *de facto* use of an internal standard
- Automatically corrects for matrix effects
- Quantification based on the generation of a response factor relating the counts per unit concentration of the analyte/standard pair
- Relies on similar chemistries, ionization efficiencies, and MS detection efficiencies
- Conceptually can use one internal standard for a diversity of analytes
- Fastest way of performing quantitative analysis

# Isotope Dilution Mass Spectrometry

- An absolute method - A method of chemical analysis that bases characterization completely on standards defined in terms of physical properties
- A definitive method - A method of exceptional scientific status which is sufficiently accurate to stand alone in the determination of a given property for the certification of a reference material

# IDMS

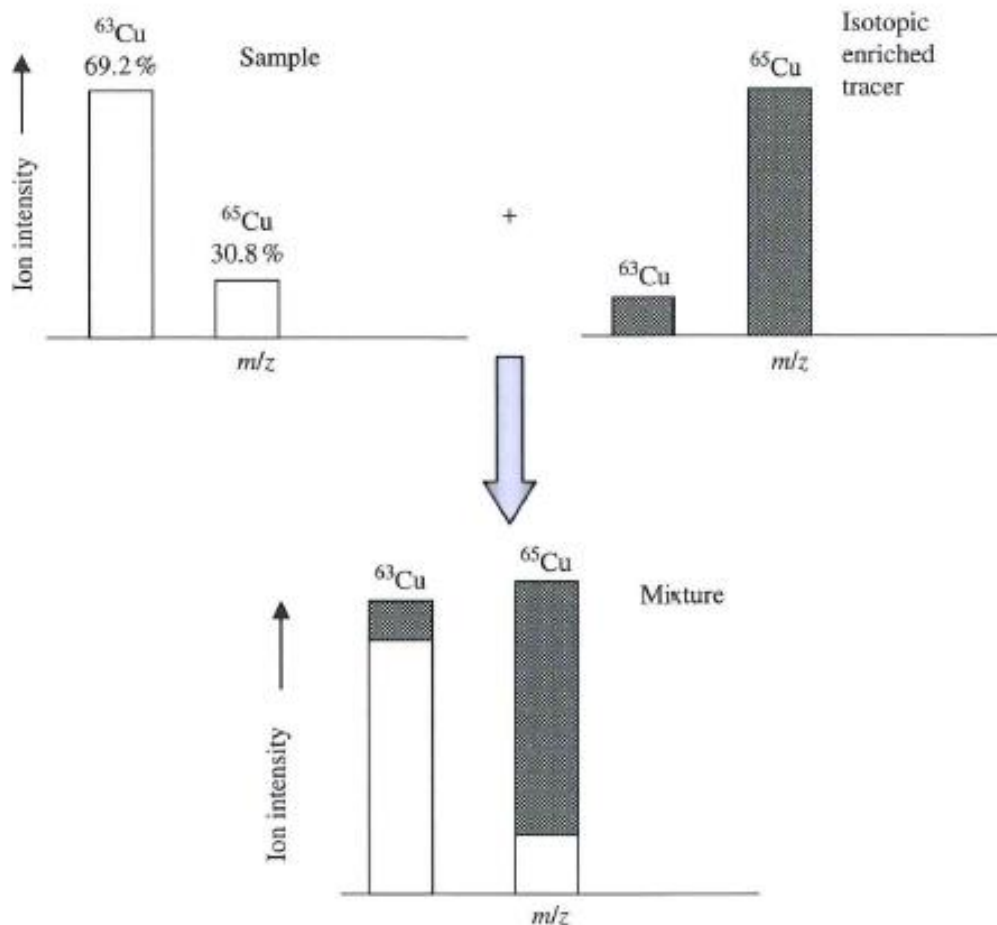


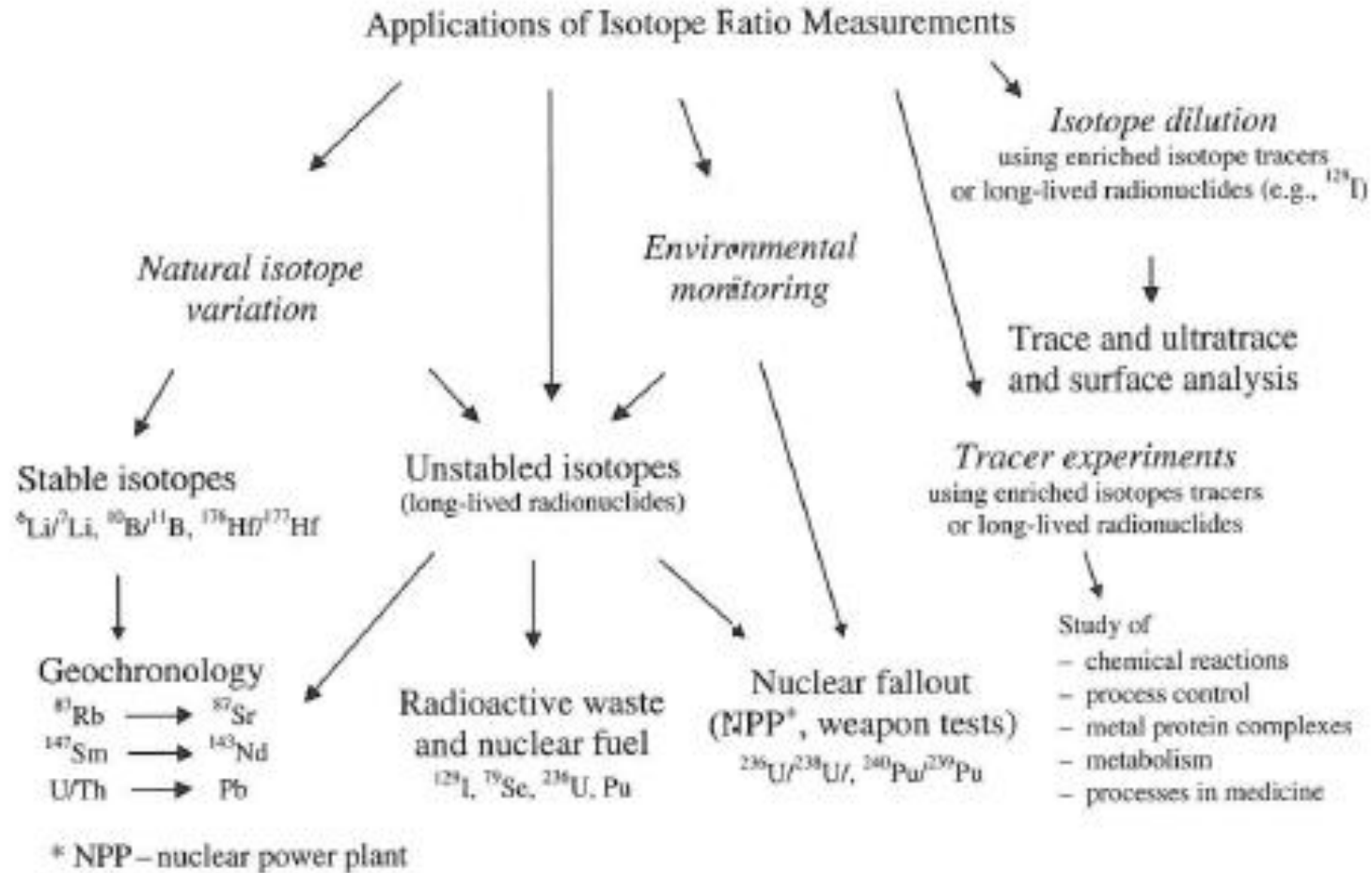
Figure 6.17 Principles of the isotope dilution technique.

$$R = \frac{N_x A_x + N_s A_s}{N_x B_x + N_s B_s}$$

R=measured ratio, N=# atoms of x=sample, s=spike, A & B=isotopic abundance of x & s

$$C_x = \frac{C_s W_s}{W_x} \frac{A_s - RB_s}{RB_x - A_x}$$

# Isotope Ratio Mass Spectrometry (IRMS)



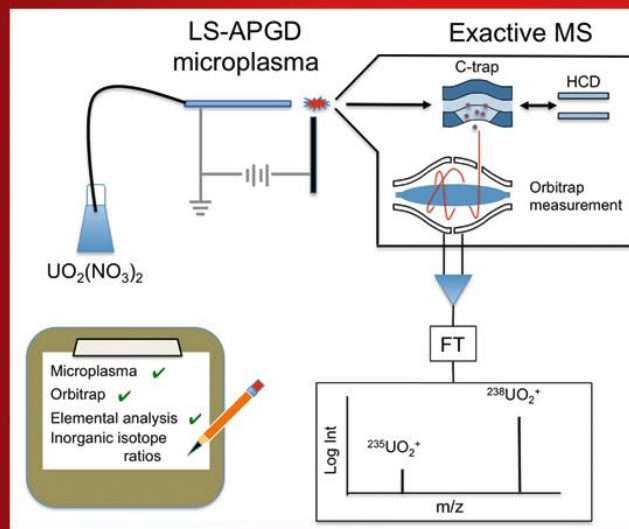
**Figure 8.1** Fields of application for isotope ratio measurements. (Modified from J. S. Becker, *J. Anal. At. Spectrom.*, **17**, 1172 (2002). Reproduced by permission of The Royal Society of Chemistry.)

# The future . . . .

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The LS-APGD microplasma/Orbitrap coupling presents promising options for isotope ratio analysis, see page 1393.

### In this Issue:

#### Articles on:

- APCI and APPI
- ETD and UVPD of Peptides and Proteins
- Digital Ion Traps
- SIMS Depth Profiling
- MALDI Imaging
- Collision Cross Sections of Amino Acids
- Quantification of Protein Modifications

# References

- J. S. Becker, “Inorganic Mass Spectrometry: Principles and Applications”, Wiley, 2007
- D. C. Harris, “Quantitative Chemical Analysis”, 6<sup>th</sup> Ed., WH Freeman, 2003
- C. Dass, “Fundamentals of Contemporary Mass Spectrometry”, Wiley, 2007
- F. Adams, R. Gijbels, and R. Van Grieken, “Inorganic Mass Spectrometry”, Wiley, 1988



# Upcoming Webinars

- Chronometry
- Nuclear Materials Analysis — Radioanalytical Methods (Destructive)
- Development of Signatures

NAMP website: [www.wipp.energy.gov/namp](http://www.wipp.energy.gov/namp)