Fundamentals of Atomic Spectroscopy: Hardware

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Introduction
Classification

Spectroscopy is a broad field with many subdisciplines, which can be classified by the type of material being analyzed. This presentation will focus on the first category, **atomic spectroscopy**.

ATOMS
Atomic spectroscopy
- AAS
- MP-AES
- ICP-OES
- ICP-MS

MOLECULES
Molecular spectroscopy
- UV-VIS
- UV-VIS-NIR
- FTIR
- Fluorescence

CRYSTALS
- X-ray crystallography

NUCLEI
- Nuclear magnetic resonance

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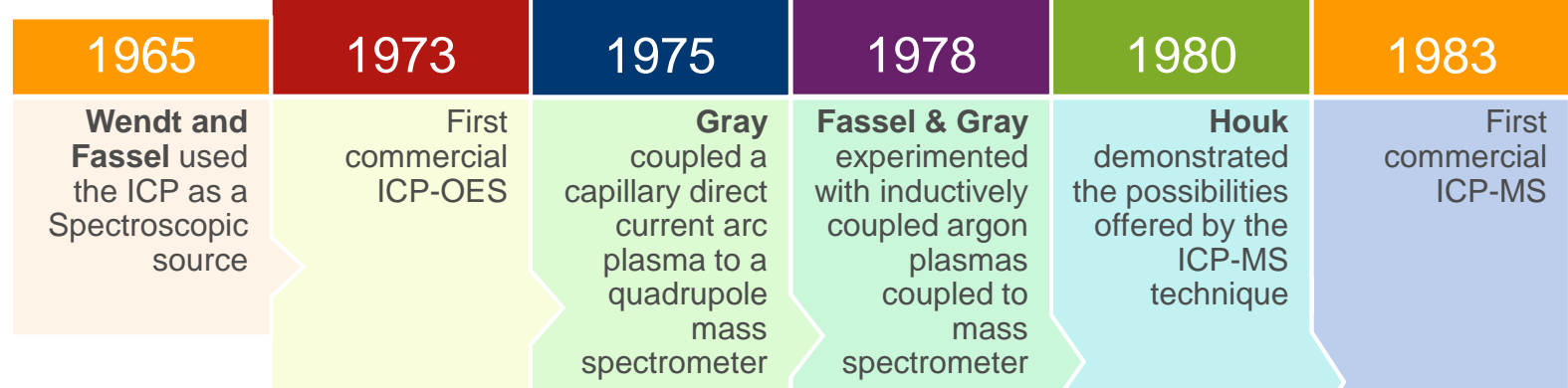RESEARCH

Introduction
General

Atomic spectroscopy includes a number of analytical techniques used to determine the **elemental composition** of a sample by examining its electromagnetic spectrum or its mass spectrum.

Atomic Spectroscopy	
Identification based on	
Electromagnetic spectrum	Mass spectrum
Atomic Absorption • Flame AAS • Graphite Furnace AAS • Vapor (Hydride) Generation AAS	
Atomic Emission • MP-AES • ICP-OES • X-ray Fluorescence (XRF)	• ICP-MS
Atomic Interference • X-ray Diffraction (XRD)	

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Introduction
Timeline of Early Developments

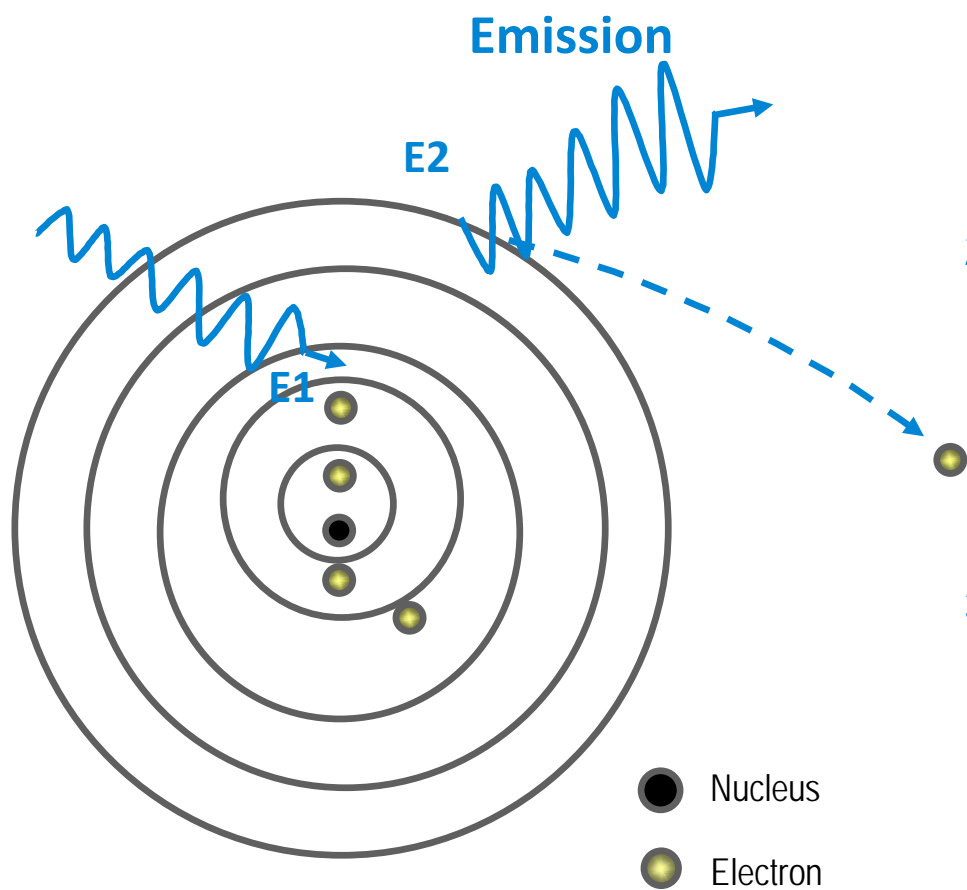| 1884	1930's	1941	1952	1961	1962	1964
Hittorf researches low pressure, electrode-less ring discharges	Lundgardh develops Flame Emission technique	**Babat** experiments with RF-ICP	**Walsh** explores potential of atomic absorption	**Reed** first major application ICP for growing crystals at high temperature	First commercial AAS	**Greenfield** used the ICP as an analytical tool

1965	1973	1975	1978	1980	1983
Wendt and Fassel used the ICP as a Spectroscopic source	First commercial ICP-OES	**Gray** coupled a capillary direct current arc plasma to a quadrupole mass spectrometer	**Fassel & Gray** experimented with inductively coupled argon plasmas coupled to mass spectrometer	**Houk** demonstrated the possibilities offered by the ICP-MS technique	First commercial ICP-MS

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Introduction
What's Measured?

Emission

E2

E1

Nucleus

Electron

1. Absorption of energy causes an electron to move to a higher energy level (E2) → **AA**

2. The excited electron will eventually drop back to the ground state and emit light at a particular wavelength (emission) → **MP-AES, ICP-OES**

3. If there is enough energy, the electron will leave the atom completely and leave behind a positively charged ion (ionization) → **ICP-MS**

See notes for details

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Atomic Absorption Spectroscopy
Principles of Operation

Atomic absorption spectroscopy (AAS) techniques rely on the fact that an atomized element will absorb light of a characteristic wavelength, elevating it from the ground state to an excited state.

The amount of light energy absorbed is proportional to the number of analyte atoms in the light path.

The technique is calibrated by introducing known concentrations of analyte atoms into the light path and plotting the absorption versus concentration curve.

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Atomic Absorption Spectroscopy
General Set Up
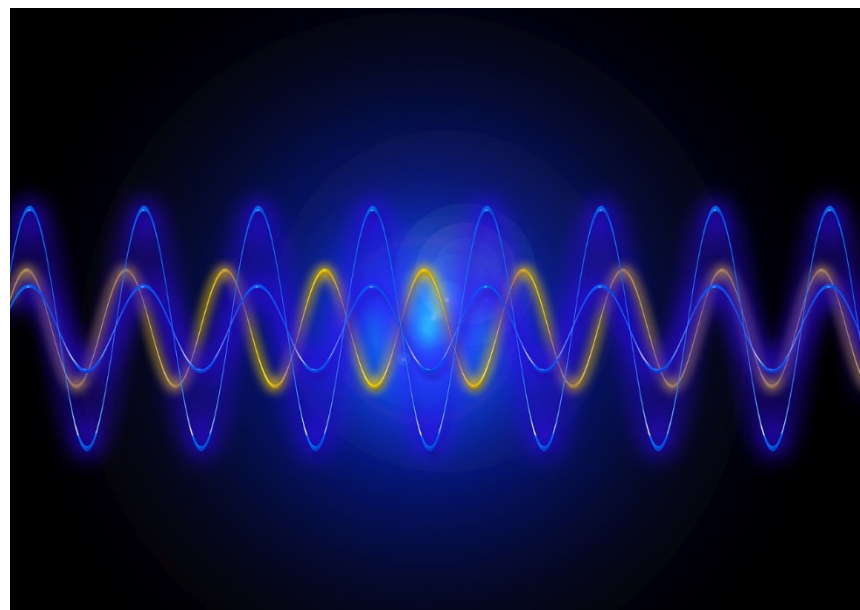
| Lamp | → | Atomizer | → | Mono-chromator | → | Detector |

- Lamp emits light for element of interest
- Atomizer converts liquid sample into free atoms which absorb energy from the lamp
- Monochromator selects wavelength used for measurement
- Detector measures light absorbed by free atoms

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Atomic Absorption Spectroscopy Lamp

The source of light primarily used with the atomic absorption technique is the hollow cathode lamp (HCL).

Typically each lamp is dedicated to the analysis of a single element, though in some cases a few elements can be combined into a single lamp.

Because of this limitation, atomic absorption is typically used for analysis of either a single element or a small number of elements.

Getter spot   Anode

Pyrex envelope   Cathode   Electrical contacts
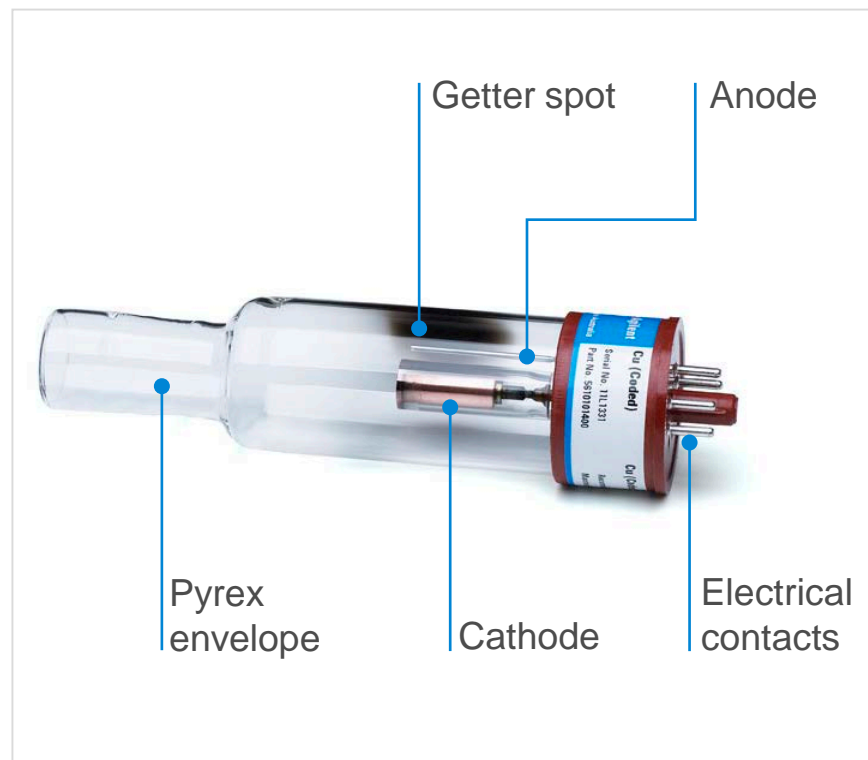
Typical hollow cathode lamp construction

See notes for details

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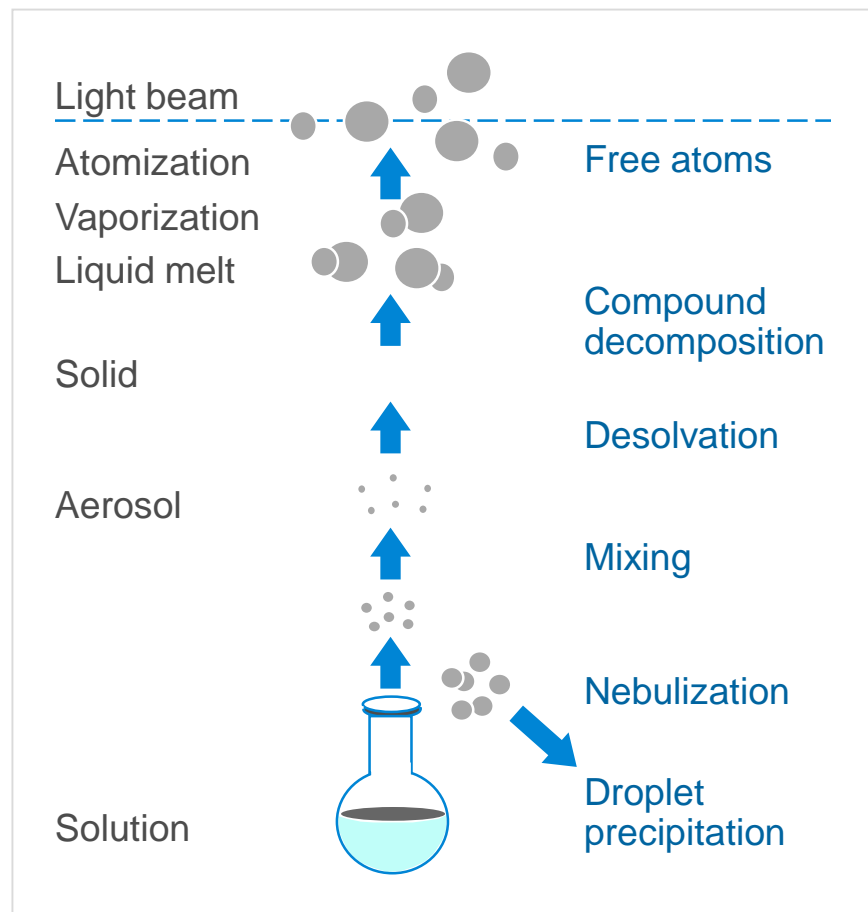
Atomic Absorption Spectroscopy
Atomizer

Atomization is the process that converts a liquid sample into free atoms.

The diagram shows the different steps that occur during atomization, starting with the element being prepared as a solution.

Element M undergoes different stages:
- Solution: MA_{liquid} (compound)
- Nebulization: MA_{liquid} (compound)
- Desolvation: MA_{solid} (A = solution anion)
- Vaporization: MA_{gas}
- Atomization: M^0
- Excitation: M^*
- Ionization: M^+

Light beam

Atomization — Free atoms

Vaporization

Liquid melt — Compound decomposition

Solid — Desolvation

Aerosol — Mixing

Nebulization

Solution — Droplet precipitation

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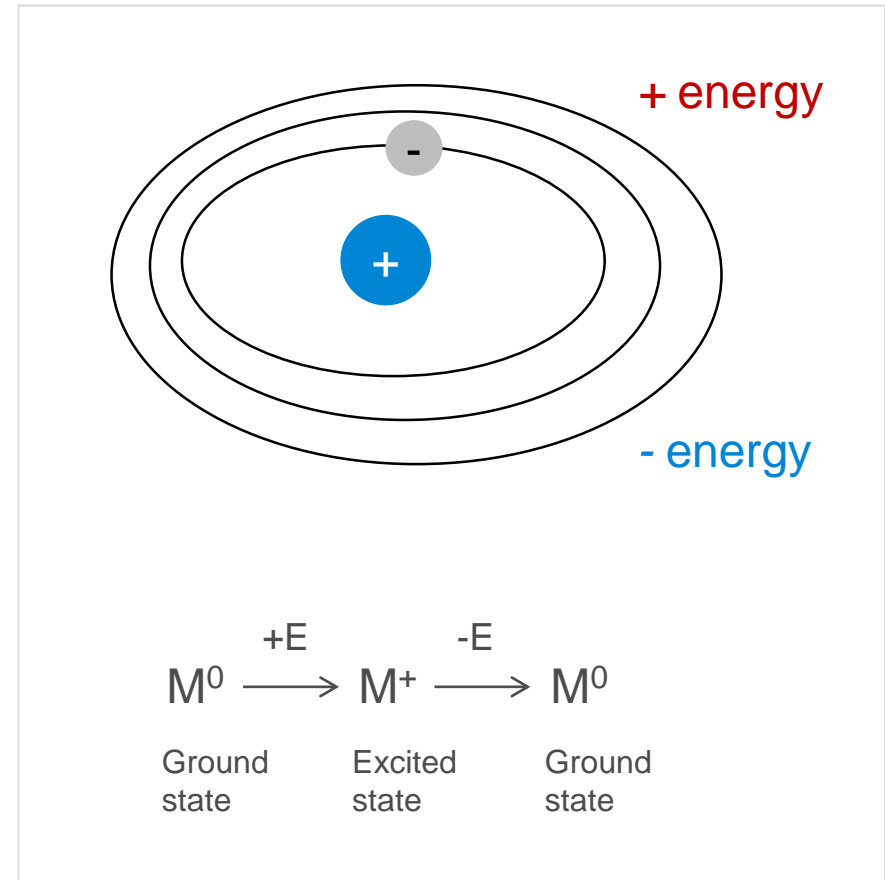
Atomic Absorption Spectroscopy
Atomizer

Atoms can absorb discrete amounts of energy:

- Heat
- Light at discrete wavelengths

An electron may change energy levels

- An atom can pick up (absorption) or release (emission) energy.
- Atom becomes "excited"
- Excitation is explained by the transition of an electron from an inner orbit (higher energy) to an outer orbit.
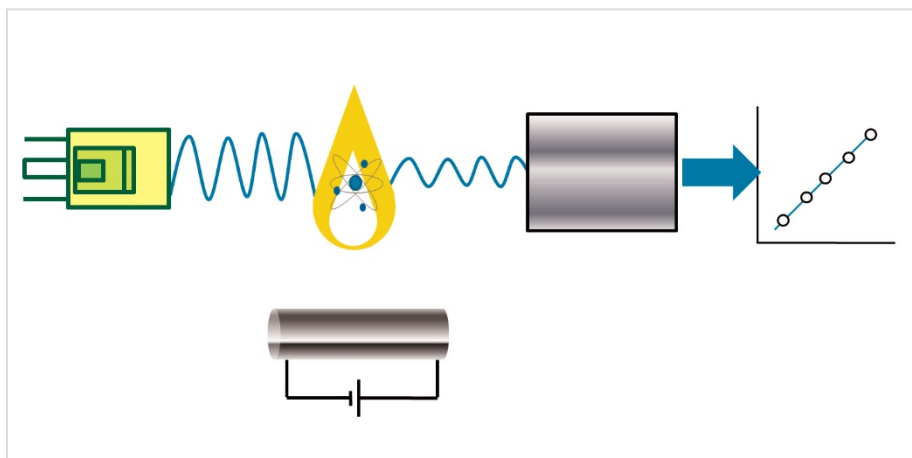
+ energy

- energy

$$M^0 \xrightarrow{+E} M^+ \xrightarrow{-E} M^0$$

Ground state   Excited state   Ground state

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Atomic Absorption Spectroscopy
Flame AAS Atomizer

In **flame AAS (FAAS)** the sample is prepared as a liquid and nebulized into the flame.

The fundamental characteristic of this technique is the atomization that happens in the flame.

Schematic diagram of flame or graphite furnace atomic absorption spectrometer system

Flame AAS
Advantages
• Short analysis time possible
• Good precision
• Easy to use
• Cheap
Limitations
• Sensitivity
• Dynamic range
• Requires flammable gases
• Unattended operation is not possible because of flammable gases
• Must not contain excessive amounts of dissolved solids

Source: Atomic spectroscopy applications in the contract environmental laboratory

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Atomic Absorption Spectroscopy
Graphite Furnace AAS Atomizer

Dissolution of sample into a liquid form is required in most cases.

Sample is injected into a graphite tube and electrothermally heated in different stages to atomize the analyte.

In graphite furnace atomic absorption (GFAAS) the atomization happens in three stages:

- Drying
- Ashing
- Atomization

Graphite furnace operation is a complementary technique to conventional flame AA and adds some advantages to the analysis.

Graphite furnace
Advantages
• High sensitivity due to − entire sample is atomized at one time − free atoms remain in the optical path longer • Reduced sample volume • Ultra trace analysis possible • Can run unattended, even overnight
Limitations
• Very slow • Fewer elements can be analyzed • Poorer precision • More chemical interferences (compared to flame AA) • Method development requires skill • Standard additions calibration required more frequently (compared to flame AA) • Expensive consumables (graphite tubes)

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Atomic Absorption Spectroscopy
Graphite Furnace AAS Atomizer

The graphite tube sits in this apparatus which supplies an inert gas and a powerful to heat the tube, which then desolvates and atomizes the sample.

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Atomic Absorption Spectroscopy
Elemental Coverage in AAS

Atomic Absorption Spectroscopy
Other Atomizers

Hydride generation technique

Suitable for elements forming volatile hydrides (As, Sn, Bi, Sb, Te, Ge and Se) when reacted with a reducing agent, such as sodium borohydride.

Advantages
• Separation of specific elements as hydrides which can eliminate matrix interference
• Good sensitivity due to 100% sampling efficiency
• Good precision
• Faster than graphite furnace AA

Limitations
• Limited to specific elements
• Some chemical interferences
• Requires specific sample preparation (analyte must be converted to a specific oxidation state)

Cold vapor technique

Used specifically for mercury (has a large enough vapor pressure at ambient temperature) which can be reduced to atomic state by a strong reducing agent, such as sodium borohydride, tin (II) chloride).

Advantages
• Eliminates many matrix interferences
• Good sensitivity due to 100% sampling efficiency
• Good precision
• Faster than graphite furnace AA

Limitations
• Limited to mercury only
• Mercury must be stabilized in solution

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Atomic Absorption Spectroscopy
## System

Key Applications

- Determination of trace metals/ impurities in oil, plants, water

- Analysis of elements in fluids, water, soil, food, serum, semiconductor material

- And many more

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Example
Flame AAS: Determination of Low Levels of Gold in Mineral Ore

Wavelength used (nm)	Characteristic concentration (mg/L)	Detection limit (mg/L)
242.8	0.079	0.0054
267.6	0.14	0.0098
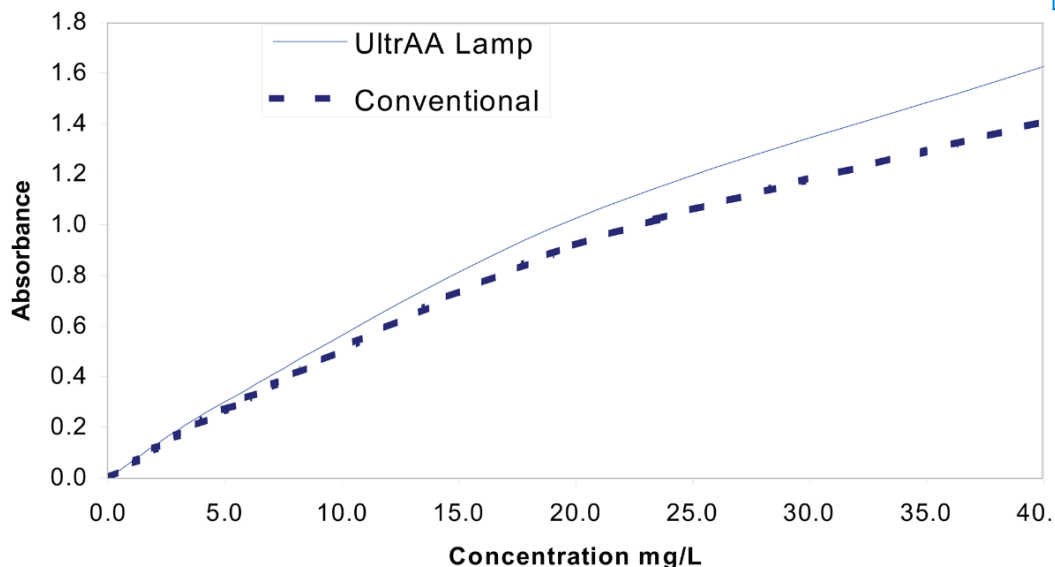
Flame AAS results for Au in mineral ore

Source: Extending the Analytical Range for Gold Using Agilent UltrAA Lamps

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Example
GF AAS: Measuring Cd, Cu, Pb, Co, Ni in Marine Invertebrates

Element	Measured limits of detection (mg/kg) (dry weight)	Tort-2; lobster hepatopancreas National Research Council Canada				CRM No 278R Mussel tissue: Mytilus edulis; Community Bureau of Reference			
		Measured	n	Certified value	% Recovery	Measured	n	Certified value	% Recovery
Cd	0.10	25.7 ± 0.92	45	26.7 ± 0.6	96	0.31 ± 0.01	54	0.348 ± 0.007	90
Cu	3.5	109 ± 4	50	106 ± 10	103	9.1 ± 0.4	53	9.45 ± 0.13	96
Pb	0.32	0.36 ± 0.04	47	0.35 ± 0.13	103	1.8 ± 0.1	51	2.00 ± 0.04	91
Co	0.13	0.55 ± 0.02	49	0.51 ± 0.09	107	0.34 ± 0.01	56	n/a	n/a
Ni	0.39	2.30 ± 0.05	49	2.5 ± 0.19	92	0.94 ± 0.04	52	n/a	n/a
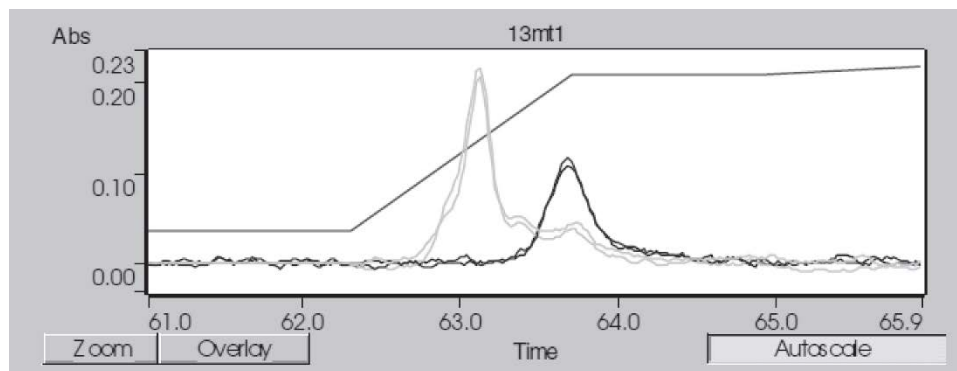
Signal graphics for Ni in CRM 786 R Mussel Tissue

Source: Sequential Determination of Cd, Cu, Pb, Co and Ni in Marine Invertebrates by Zeeman GFAAS

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Example
Hydride Generation AAS: Determination of As, Sb and Se

Sample preparation for As and Sb
One sample preparation for both elements: 5 mL sample placed in 50 mL volumetric, 25 mL HCl added.
• Mixed and cooled. 5 mL 20% urea added • Mixed and cooled. 2.5 mL 20% KI added • Diluted to mark with D.I. water. • Analyzed for As and Sb after 30 minutes

Sample	Conc. (ppb)	%RSD	Mean abs
Blank	0.0		0.008
Standard 1	2.0	2.0	0.062
Standard 2	5.0	0.9	0.148
Standard 3	10.0	0.6	0.262
Standard 4	20.0	1.0	0.455
Standard 5	40.0	0.4	0.70

Sample preparation and typical calibration data for As using hydride generation

Source: Determination of As, Sb and Se in Difficult Environmental Samples by Hydride Generation

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Atomic Emission Spectroscopy
General

Due to the limitations in AAS, techniques that don't require dedicated lamps for each element have come into use. These techniques, called **atomic emission spectroscopy (AES)**, rely on the fact that once an atom of a specific element is excited (as in atomic absorption), it emits light in a characteristic pattern of wavelengths (an emission spectrum) as it returns to the ground state.

The flame is not an ideal excitation source for atomic emission. Therefore hotter sources are used.

We will discuss the following techniques:

- Microwave plasma atomic emission spectroscopy (MP-AES)
- Inductively coupled plasma optical emission spectroscopy (ICP-OES)

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Atomic Emission Spectroscopy
Microwave Plasma Atomic Emission Spectroscopy

Nitrogen plasma is used to desolvate, atomize, and excite the atoms in the liquid sample that has been nebulized into it. The nitrogen plasma is considerably hotter (up to 5,000° K) than the air-acetylene flame used in AA.

The atomic emission is quite strong for most elements, leading to improved detection capability and linear dynamic range over flame AA for most elements.

The intensity of the light emitted is measured using optical detection at the wavelengths characteristic of the elements of interest.

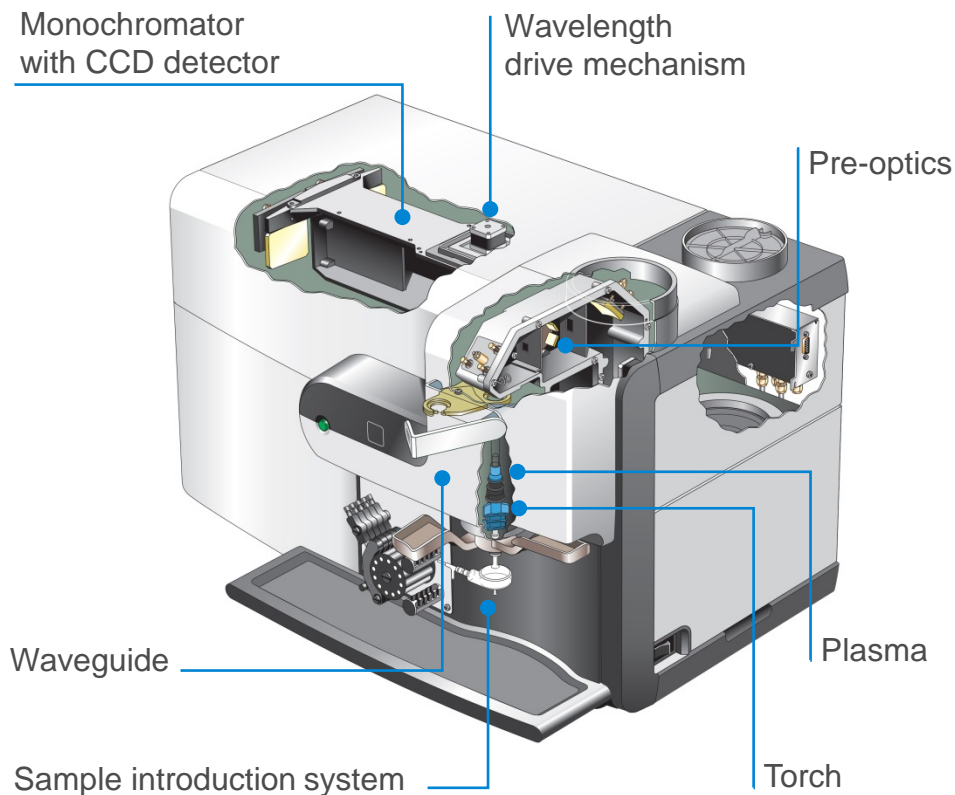| MP-AES |
| --- |
| **Advantages** |
| • Safe (no flammable gas)
 • Low operating costs as nitrogen can be extracted from compressed air using a nitrogen generator
 • No lamps required for analysis
 • Identification and quantitation of virtually all metals and many metalloids.
 • Better performance than flame AAS |
| **Limitations** |
| • Higher initial cost than AAS
 • More interferences compared with flame AA (including spectral interferences)
 • Not as sensitive as graphite furnace AAS or ICP-MS
 • Not as productive as ICP-OES
 • No isotope determination |

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Microwave Plasma Atomic Emission Spectroscopy System

Key Applications

- Trace elements in geological samples

- Metals in soil extracts

- Major elements in food and beverages

- Analysis of petroleum

- Analysis of waste water

Monochromator with CCD detector

Wavelength drive mechanism

Pre-optics

Plasma

Torch

Waveguide

Sample introduction system
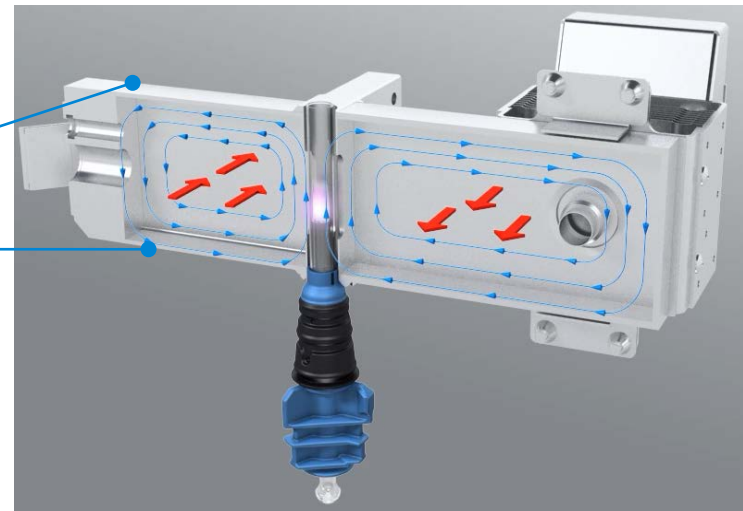
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Microwave Plasma Atomic Emission Spectroscopy
How Does It Work?

Agilent MP-AES runs from nitrogen extracted from air using a nitrogen generator.

- Axial magnetic and radial electrical fields sustain the nitrogen plasma
- Sample aerosol is introduced into nitrogen plasma

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Microwave Plasma Atomic Emission Spectroscopy
How Does It Work?

- Axial emission from the nitrogen plasma is directed into the fast-scanning monochromator optics
- Wavelength-specific emissions are detected using a high-efficiency CCD

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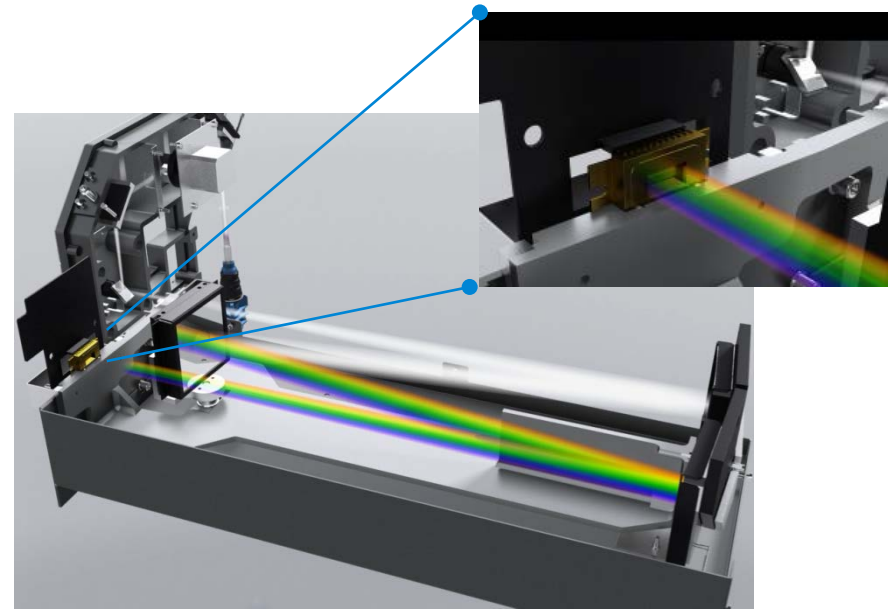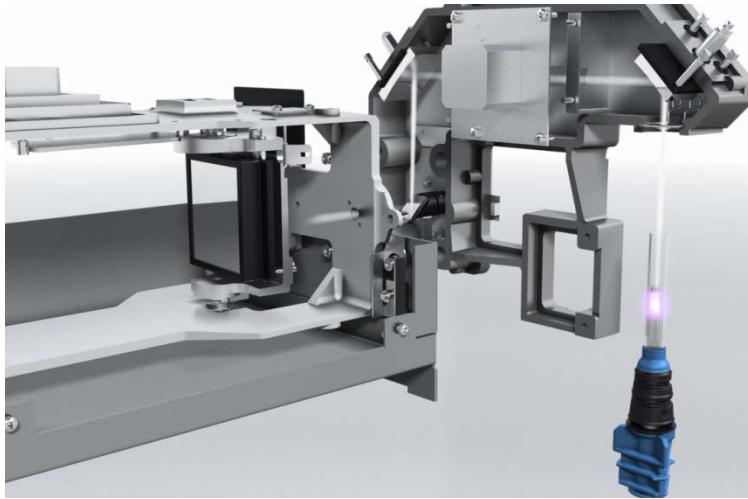
Microwave Plasma Atomic Emission Spectroscopy
Determination of Nutrients in Soil (Multielement Testing)

	Cu		Fe		Mn		Zn	
Wavelength (nm)	324.754	324.7	259.94	372	257.61	280.1	213.857	213.9
Technique	MP-AES	FAAS	MP-AES	FAAS	MP-AES	FAAS	MP-AES	FAAS
Measured conc. µg/g								
SSTD-Trail 1	1.44	1.42	7.76	8.44	24.26	26.22	0.64	0.62
SSTD-Trail 1	1.46	1.45	7.96	8.24	24.40	25.96	0.64	0.64
SSTD-Trail 1	1.44	1.42	8.08	8.64	23.70	26.50	0.62	0.58
Av. µg/g	1.45	1.43	7.93	8.44	24.12	26.23	0.63	0.61
Standard dev.	0.01	0.02	0.16	0.20	0.37	0.27	0.01	0.03

*MP-AES results for Cu, Fe, Mn, and Zn in DTPA extraction of soil, compared to FAAS*

Source: Determination of available nutrients in soil using the Agilent 4200 MP-AES

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Microwave Plasma Atomic Emission Spectroscopy
Measuring Major and Minor Elements in Milk

Element	Certified Values (g/kg)	Uncertainty (g/kg)	Result (g/kg)	Recovery (%)
Ca	13.9	0.7	14.21	102
K	17	0.8	16.66	98
Mg	1.26	0.07	1.31	104
Na	4.19	0.23	4.25	101
P	11	0.6	11.27	102

	Certified Values (g/kg)	Uncertainty (mg/kg)	Result (mg/kg)	Recovery (%)
Zn	44.9	2.3	45.89	102
Fe	53	4	50.51	95
Cu	5	0.23	5.13	103
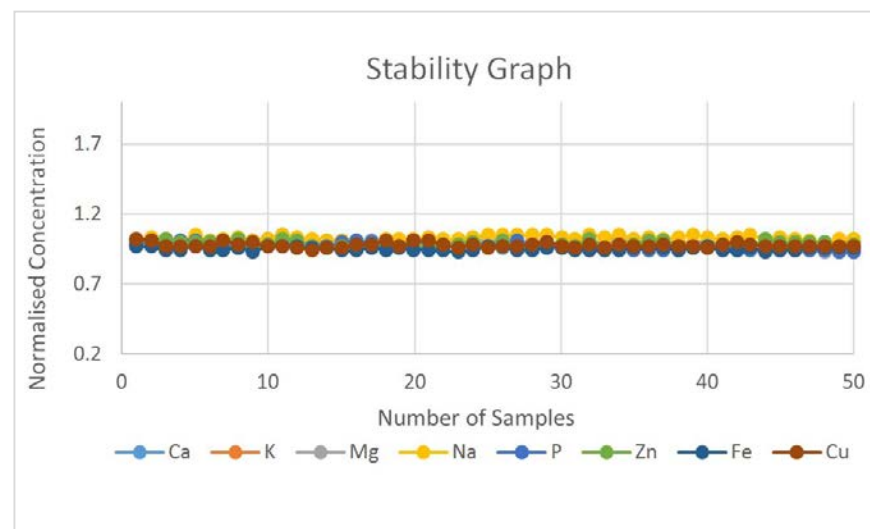
Determination of Ca, K, Mg, Na, P, Fe, Zn and Cu in TMAH, Triton X-100, EDTA and ionization buffer by MP-AES 4200

Source: Measuring major and minor elements in milk using the Agilent MP-AES 4200

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Inductively Coupled Plasma Optical Emission Spectroscopy
Principles of Operation

An argon inductively coupled plasma (hotter than MP, up to 10,000° K) is used to desolvate, atomize, and excite the atoms in the liquid sample that has been nebulized into it.

The intensity of the light emitted is measured using optical detection at the wavelengths characteristic of the elements of interest.

ICP-OES is capable of measuring both atomic and ionic emission so more wavelengths can be monitored

These measurements can be compared to a standard to quantify the concentration of the elements in the sample.

ICP- OES
Advantages
• Fastest sample throughput
• Simultaneous multi-element analysis (up to 73 elements)
• Wide dynamic range (from sub-ppb to % level)
• Tolerates complex matrices
• Low argon gas consumption
• Safe (no flammable gas)
Limitations
• Higher initial costs than AAS or MP-AES
• More spectral interferences compared with MP-AES
• Not as sensitive as graphite furnace AAS or ICP-MS
• No isotope determination

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Inductively Coupled Plasma Optical Emission Spectroscopy
General Set Up

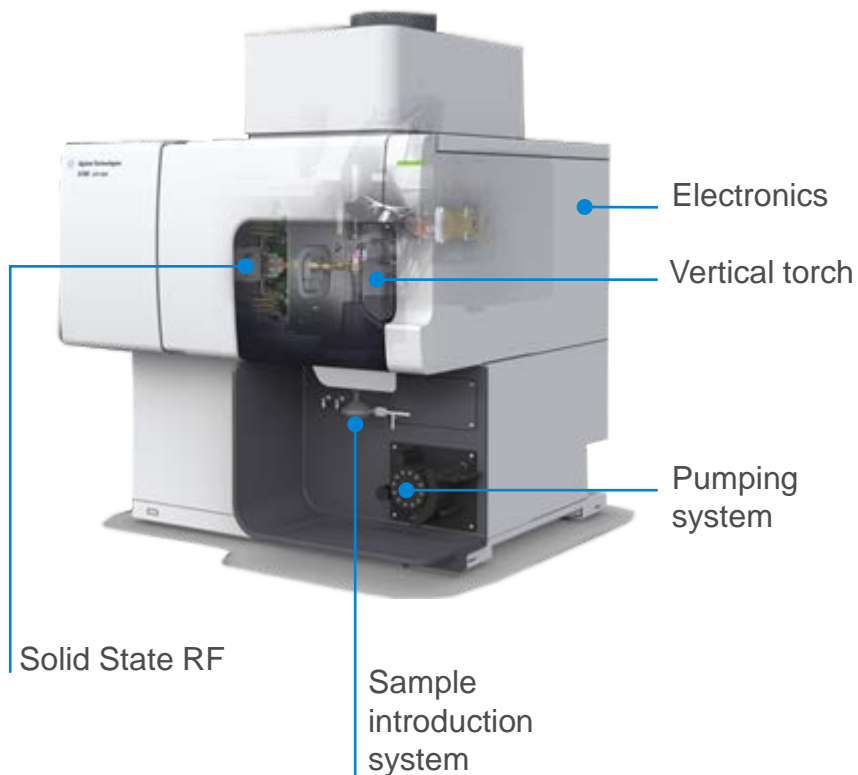Argon plasma   Spectrometer   Quantification
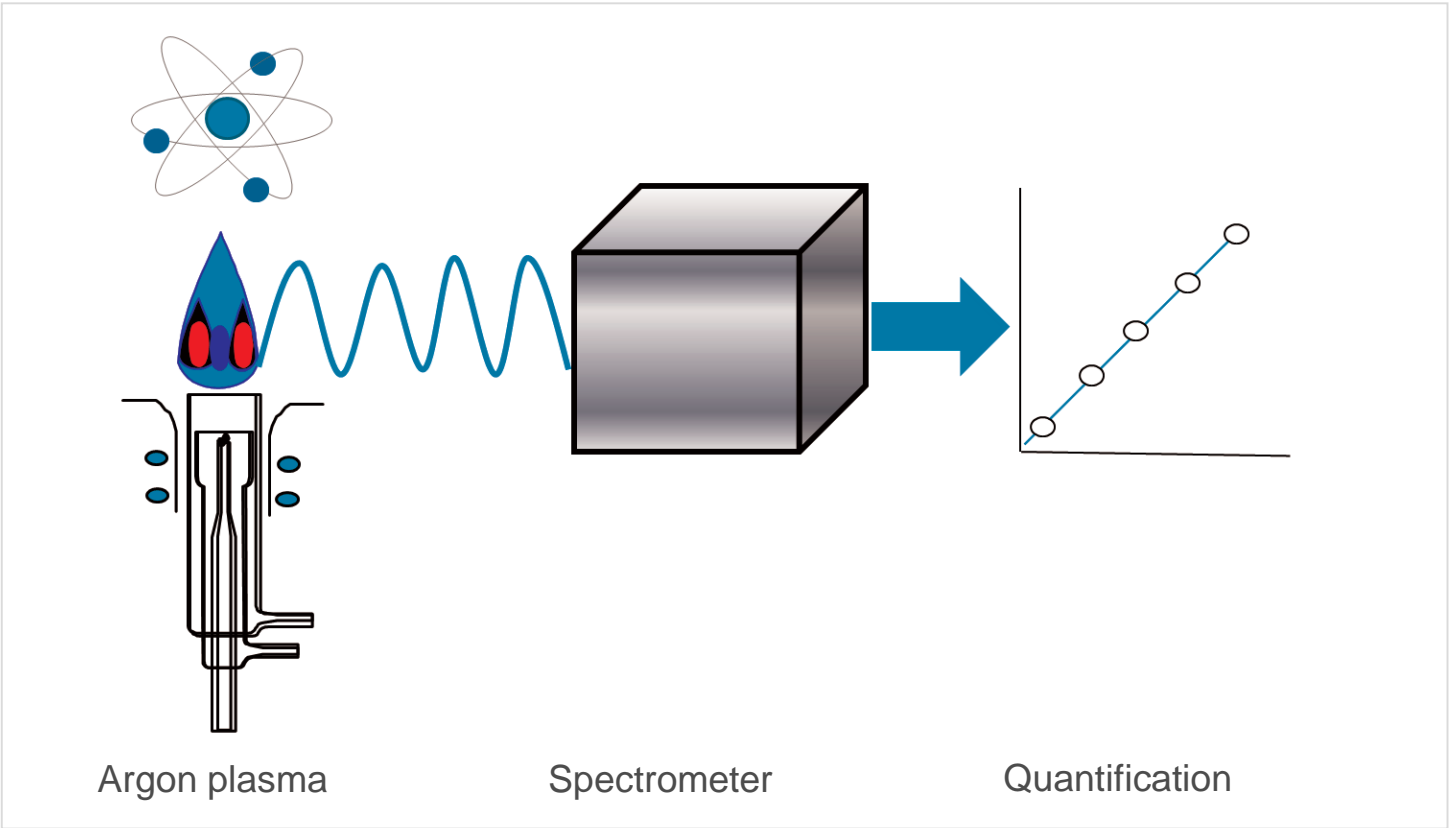
Plasma torch can be viewed axially or radially. Some "dual view" instruments allow viewing of both orientations, depending on the analysis being performed. (Axial view gives longer path length and thus greater sensitivity.)

Simplified schematic diagram of ICP-OES spectrometer system

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Inductively Coupled Plasma Optical Emission Spectroscopy System

Key Applications

- Monitoring of water/wastewater/solid wastes

- Determination of trace elements in water

- Mercury monitoring in environmental samples

- Quantitative analysis of multiple elements in water/soil/sediment environment samples

- Analysis of soil – analysis of micronutrient content (Agriculture)

- Determination of precious metals and gold

Electronics

Vertical torch

Pumping system

Solid State RF

Sample introduction system

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Inductively Coupled Plasma Optical Emission Spectroscopy
Analysis of Milk Powder

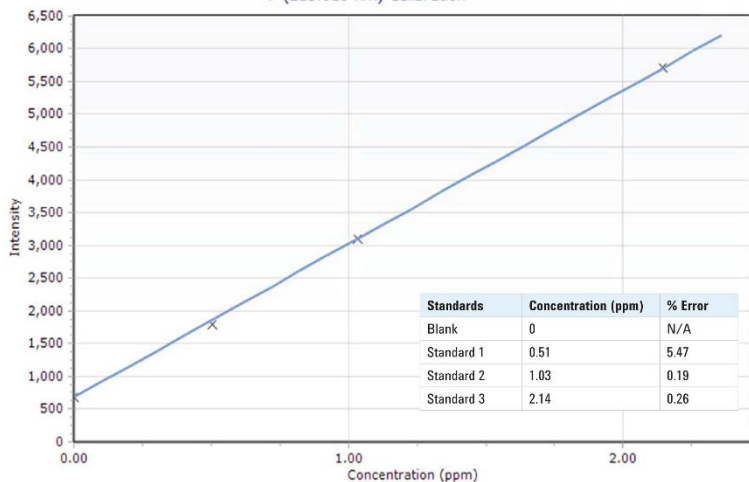| Element	Certified value (mg/kg)	Measured value (mg/kg)	Recovery (%)
Major nutrients			
K 766.491	13630	13070	96
Ca 315.887	9220	9750	106
P 213.618	7800	7160	92
Na 589.592	3560	3530	99
S 181.792	2650	2650	100
Minor and trace nutrients			
Mg 279.078	814	749	92
Zn 202.548	28.0	28.9	103
Sr 421.552	4.35	4.37	101
Fe 259.940	1.8	1.9	107
Cu 327.395	0.46	0.46	100
Mo 204.598	0.29	0.27	92
Mn 257.610	0.17	0.18	103

Analysis of NIST milk powder 8435 SRM using the 5100 SVDV ICP-OES

Source: Analysis of milk powders based on Chinese standard method using the Agilent 5100 SVDV ICP-OES

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Inductively Coupled Plasma Optical Emission Spectroscopy
Analysis of Biodiesel Oil

P (213.618 nm) Calibration

Standards	Concentration (ppm)	% Error
Blank	0	N/A
Standard 1	0.51	5.47
Standard 2	1.03	0.19
Standard 3	2.14	0.26

Calibration curve for P 213.618 nm line, using FBC background correction, shows excellent linearity across the calibrated range, with a correlation coefficient of 0.99986.

Element	λ (nm)	Background correction used	Calibration range (mg/kg)	Correlation coefficient	MDL (ppm)
Ca	422.673	Fitted	0-2	0.99995	0.004
K	766.491	FACT	0-2	0.99996	0.008
K	766.491	Fitted	0-2	0.99935	0.048
Mg	279.553	Fitted	0-2	0.99994	0.0004
Na	588.995	FACT	0-2	0.99991	0.002
Na	588.995	Fitted	0-2	0.99996	0.048
P	213.618	Fitted	0-2	0.99996	0.013
S	181.972	Fitted	0-2	0.99967	0.31

Agilent 5100 ICP-OES wavelengths and calibration parameters. All results are shown in solutions.

Source: Analysis of biodiesel oil (as per ASTM D6751 & EN 14214) using the Agilent 5100 SVDV ICP-OES

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Inductively Coupled Plasma Mass Spectrometry
General

ICP-MS combines two advantages:

1. Argon ICP as a highly efficient ion source
2. A mass spectrometer for fast scanning, high ion transmission and unit mass resolution

The main difference to ICP-OES is to analyze atomic ions. Most elements have the first ionization potential of 4 to10 eV, which are efficiently ionized in argon ICP.

Ions are passed into the high vacuum region for separation and detection. Photons and neutral species are rejected.

The mass spectrometer separates ions based on their mass-to-charge ratio (m/z).

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Inductively Coupled Plasma Mass Spectrometry
General

An electron multiplier detector generates a pulse for each ion reaching it.

Since the charge on a singly ionized element is 1, the *m/z* is equal to the mass, so ICP-MS measures the elements as a simple spectrum of characteristic atomic (isotopic) mass from ^{6}Li to ^{238}U.

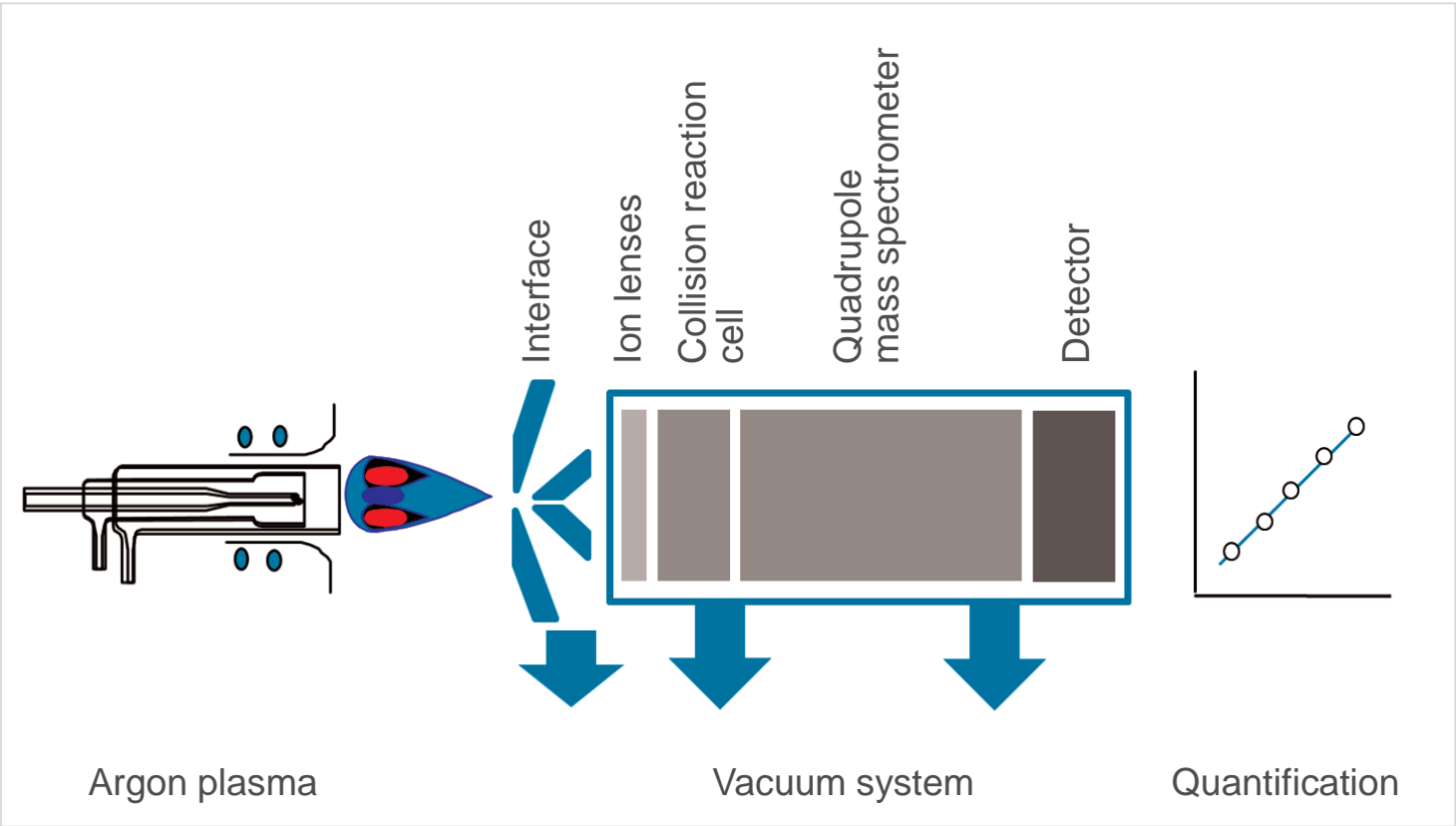| ICP-MS |
| --- |
| **Advantages** |
| • Most sensitive technique
• Multi-element analysis
• Isotopic information (IR, ID analysis)
• Wide dynamic range
• Tolerates complex matrices |
| **Limitations** |
| • Less matrix tolerance than ICP-OES
• Most expensive technique (purchase and running costs)
• Subject to isobaric interferences |

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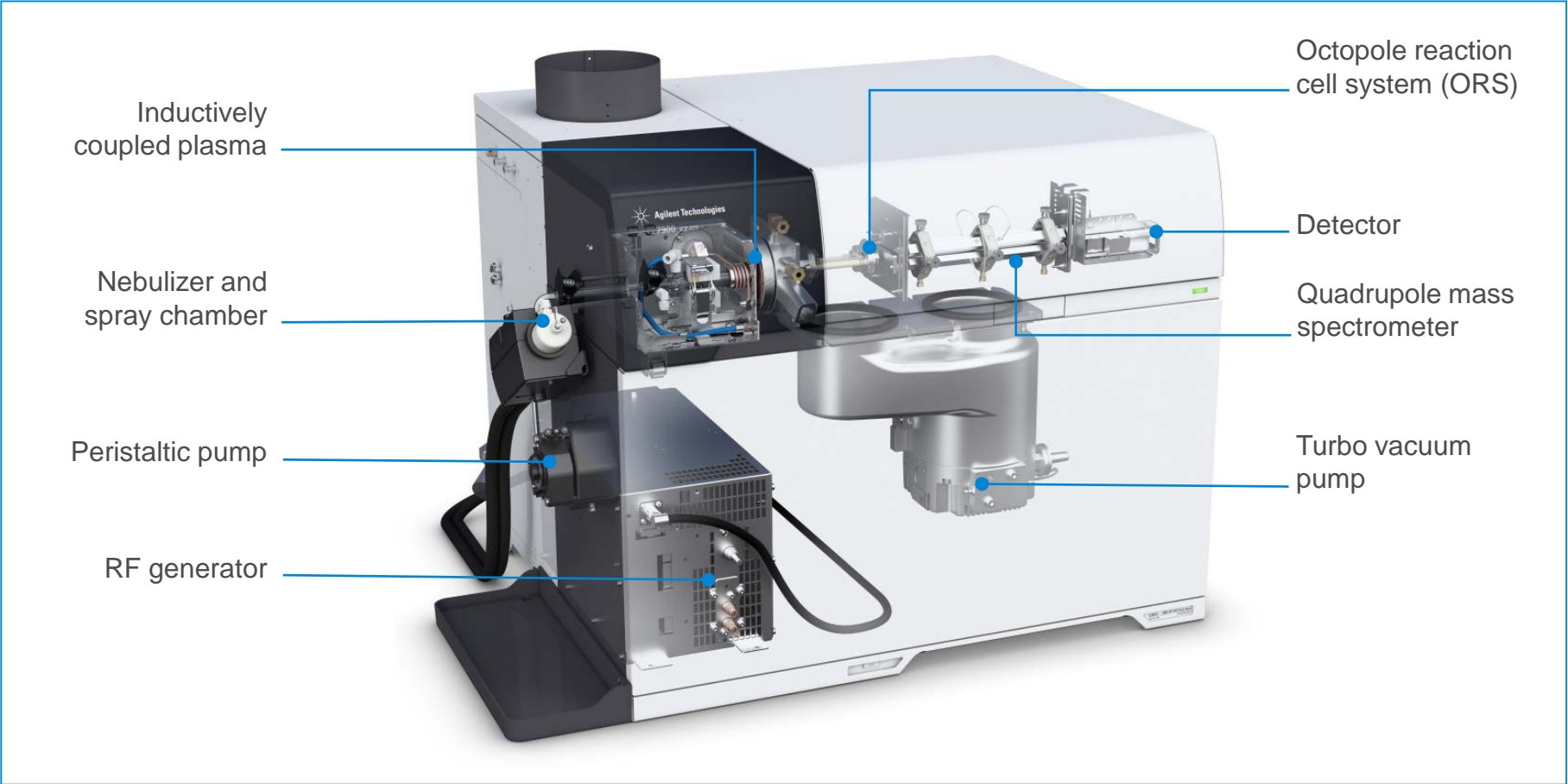& INSTITUTIONAL
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Inductively Coupled Plasma Mass Spectrometry
General Set Up

Simplified schematic diagram of the major components of a quadrupole ICP-MS system.

Interface

Ion lenses

Collision reaction cell

Quadrupole mass spectrometer

Detector

Argon plasma

Vacuum system

Quantification

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Inductively Coupled Plasma Mass Spectrometry System

Octopole reaction cell system (ORS)

Inductively coupled plasma

Detector

Nebulizer and spray chamber

Quadrupole mass spectrometer

Peristaltic pump

Turbo vacuum pump

RF generator

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Inductively Coupled Plasma Mass Spectrometry
How Helium Collision Cell Mode Removes Spectra Interference

Interference removal using He mode and Kinetic Energy Discrimination (KED)

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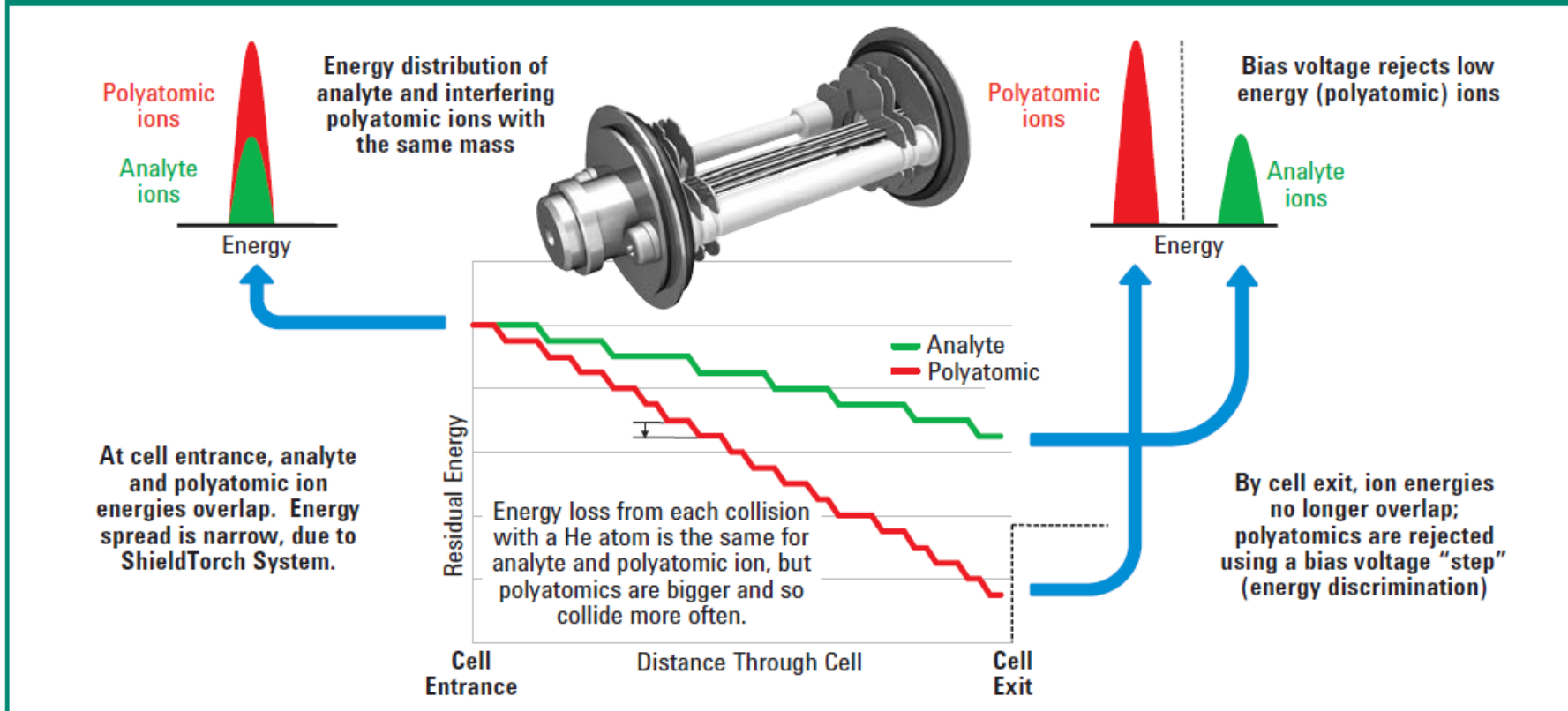
Inductively Coupled Plasma Mass Spectrometry
ICP-MS as a Chromatography Detector

In addition to its common use as a standalone metals analyser, ICP-MS is increasingly applied as a detector for a range of chromatographic separation methods

- Capillary electrophoresis (CE)

- Field-flow fractionation (FFF)

- Ion chromatography (IC)

- Liquid chromatography (HPLC)

- Gas chromatography (GC)

In this configuration, the front-end technique separates the different species (with time), and the ICP-MS operates as a mass selective detector to measure the element(s) associated with the compound(s) of interest as they elute from the chromatograph.
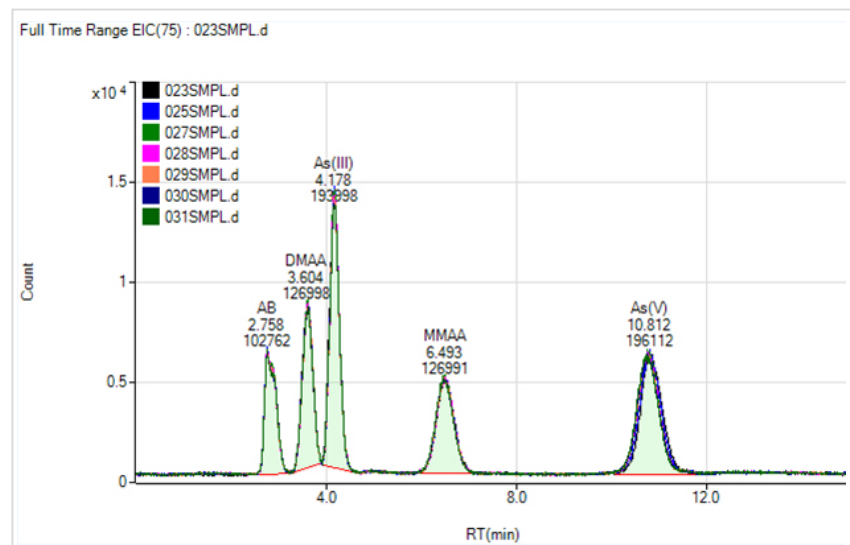
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Inductively Coupled Plasma Mass Spectrometry
Speciation with LC-ICP-MS and GC-ICP-MS

HPLC-ICP-MS application examples:

- Inorganic vs. organic arsenic

- Organo-tin

- Methyl-mercury

GC-ICP-MS examples:

- Pesticides

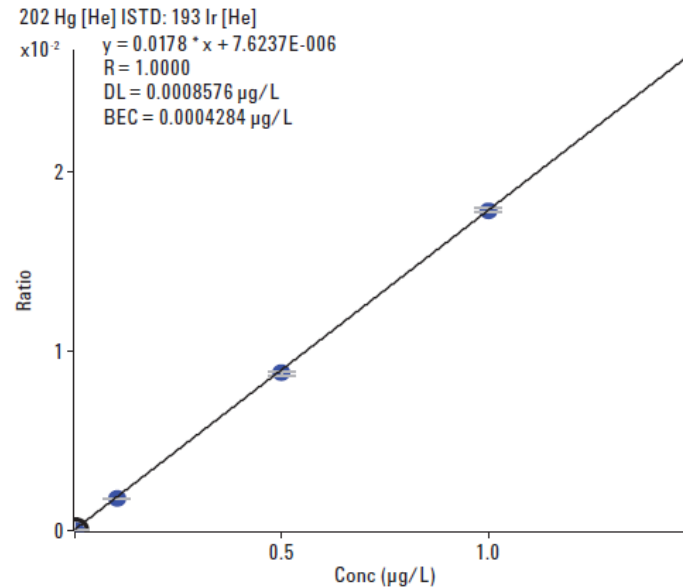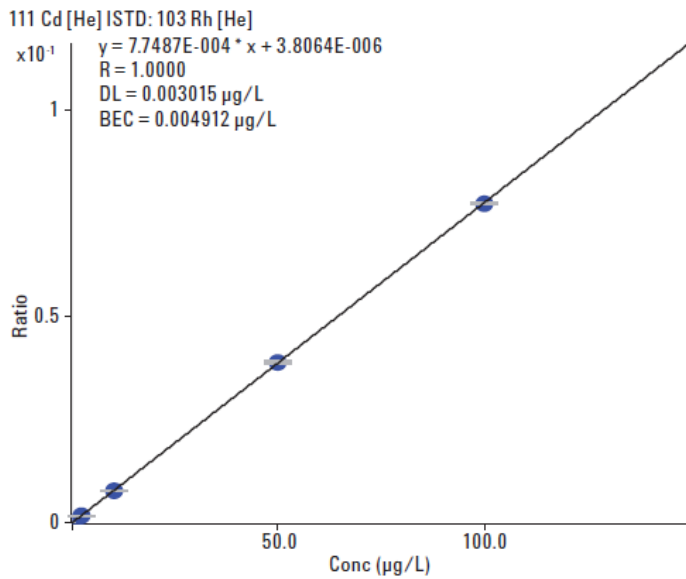- OP nerve agent residues

- PBDEs

- Nanoparticles

Seven overlaid chromatograms of apple juice spiked with 500 ng/L As standard.

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Inductively Coupled Plasma Mass Spectrometry
Drinking Water Analysis

Most developed countries have enacted regulations and monitoring programs to ensure that the supply of drinking water is free from potentially harmful chemicals. The fast, multi-element technique of ICP-MS is widely used for this.

111 Cd [He] ISTD: 103 Rh [He]
$y = 7.7487E\text{-}004 * x + 3.8064E\text{-}006$
$R = 1.0000$
DL = 0.003015 µg/L
BEC = 0.004912 µg/L

202 Hg [He] ISTD: 193 Ir [He]
$y = 0.0178 * x + 7.6237E\text{-}006$
$R = 1.0000$
DL = 0.0008576 µg/L
BEC = 0.0004284 µg/L

Calibration plot of Cd and Hg

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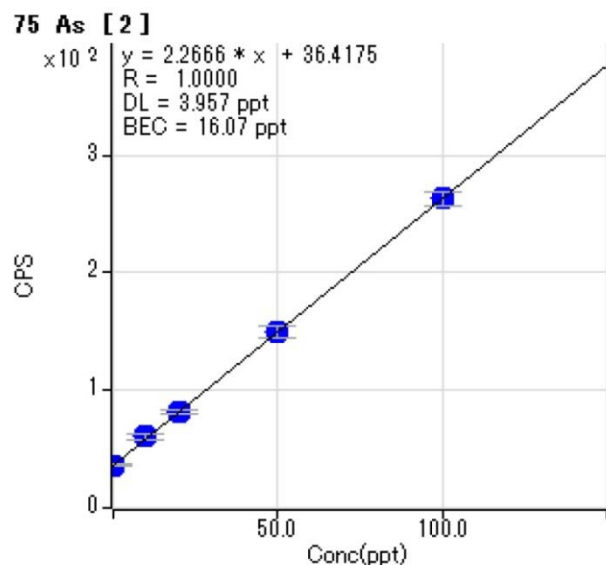
Inductively Coupled Plasma Mass Spectrometry
Trace Metallic Impurity Analysis in High Purity HCl

HCl is frequently used to remove metallic impurities on the surface of silicon wafers. The manufacturing process of semiconductor devices requires routine monitoring of ultra-trace contaminants in HCl.

75 As [2]

$y = 2.2666 * x + 36.4175$
$R = 1.0000$
$DL = 3.957$ ppt
$BEC = 16.07$ ppt

As, which suffers ArCl+ interference, can be measured at trace levels.

Element	m/z	Mode	DL ppt	BEC ppt
Li	7	cool	0.016	0.004
Be	9	no gas	0.13	0.11
B	11	no gas	4.5	9.7
Na	23	cool	0.44	1.3
Mg	24	cool	0.11	0.22
Al	27	cool	0.79	1.1
K	39	cool/NH_3	0.40	0.50
Ca	40	cool/NH_3	1.1	2
As	75	He	4.0	16

Source: Direct analysis of trace metallic impurities in high purity hydrochloric acid by Agilent 7700s ICP-MS

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Summary
Atomic Spectroscopy Techniques

	AAS		MP-AES	ICP-OES	ICP-MS	
	FAAS	**GFAAS**			**SQ**	**QQQ**
Detection Limits	100's ppb	10's-100's ppt	ppb – 10's ppb	100's ppt-ppb	<ppt	<ppt
Measurement mode	Sequential	Sequential	Sequential	Simultaneous	Sequential (MS)	Sequential (*MS/MS for difficult interference problems)
Maximum samples/day	100-200 (~6 elements)	50-100 (~2 elements)	300-500 (~10 elements)	2000-2500 (50+ elements)	750-1000 (~50 elements)	500-750 (~50 elements)
Working dynamic range	3-4	2-3	4-5	7-8	10-11	9
Operator skill required	Low	Mid	Low	Mid	High	Highest

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Abbreviations

Abbreviation	Definition
A	absorbance
AAS	atomic absorption spectroscopy
AES	atomic emission spectroscopy
b	path length (cm)
c	speed of light (3×10^8 ms^{-1})
ε	extinction coefficient or molar absorption (Lmol^{-1}cm^{-1})
E	oscillating electric field
E	energy
h	Planck's constant (6.62×10^{-34} Js)
I	transmitted radiation
I$_0$	incident radiation

Abbreviation	Definition
ICP-OES	inductively coupled plasma – optical emission spectroscopy
ICP-MS	inductively coupled plasma – atomic mass spectrometry
SQ	single quadrupole mass spectrometry
QQQ	triple quadrupole mass spectrometry
M	oscillating magnetic fields
MP-AES	microwave plasma atomic emission spectroscopy
T	transmittance
v	frequency (s^{-1})
XRF	X-ray fluorescence
XRD	X-ray diffraction

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Publication	Title	Pub. No.
Primer	Atomic spectroscopy applications in the contract environmental laboratory	5991-5326EN
Application	Extending the analytical range for gold using UltrAA lamps	SI-A-1138
Application	Sequential Determination of Cd, Cu, Pb, Co and Ni in Marine Invertebrates by Zeeman GFAAS	SI-A-1361
Application	Determination of As, Sb and Se in Difficult Environmental Samples by Hydride Generation	SI-A-1299
Application	Determination of available nutrients in soil using the Agilent 4200 MP-AES	5991-5675EN
Application	Measuring major and minor elements in milk using the Agilent MP-AES 4200	5991-5959EN
Application	Analysis of milk powders based on Chinese standard method using the Agilent 5100 SVDV ICP-OES	5991-4900EN
Application	Analysis of biodiesel oil (as per ASTM D6751 & EN 14214) using the Agilent 5100 SVDV ICP-OES	5991-5333EN
Application	Arsenic speciation analysis in apple juice using HPLC-ICP-MS with the Agilent 8800 ICP-QQQ	5991-0622EN
Application	Agilent 7900 ICP-MS simplifies drinking water analysis	5991-4938EN
Application	Direct analysis of trace metallic impurities in high purity hydrochloric acid by Agilent 7700s ICP-MS	5990-7354EN
Application Compendium	Agilent Speciation Handbook (2nd Edition)	5990-9473EN
Brochure	Atomic Spectroscopy Portfolio Brochure	5990-6443EN
Web	CHROMacademy – free access for students and university staff to online courses	
Videos & Images	www.agilent.com/chem/teachingresources	

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THANK YOU

Publication Number: 5991-6593EN

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