Marianne Liebi– Material Science at Large Scale Facilities

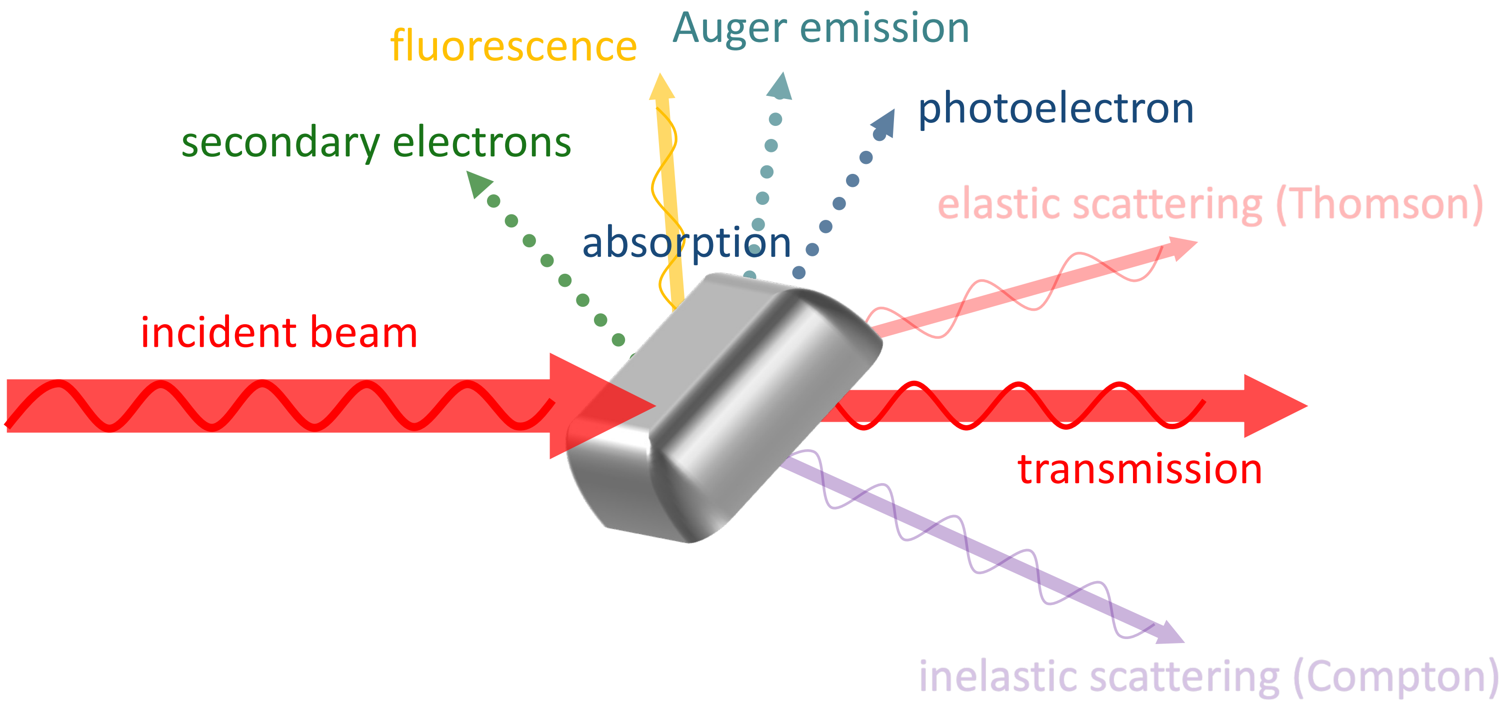
X-ray Fluorescence Spectroscopy (XRF)

EPFL Master Course 2024 MSE435

Course program

09.09.24	Introduction, sources, beamlines, detectors	Steven Van Petegem
16.09.24	Holiday	
23.09.24	Excursion to PSI	Steven Van Petegem / Marianne Liebi
30.09.24	Interaction with matter	Steven Van Petegem
07.10.24	Fluorescence	Marianne Liebi
14.10.24	Diffraction I	Steven Van Petegem
21.10.24	Break	
28.10.24	Small angle x-ray scattering	Marianne Liebi
04.11.24	Diffraction II / Magnetic scattering	Steven Van Petegem
11.11.24	XANES/EXAFS	Marianne Liebi
18.11.24	Phase contrast / Tomography	Steven Van Petegem
25.11.24	Coherent imaging	Marianne Liebi
02.12.24	Neutron imaging	Steven Van Petegem
09.12.24	PEEM/Muon	Steven Van Petegem
16.12.24	Case study presentations	Steven Van Petegem / Marianne Liebi

Interaction of X-ray with matter

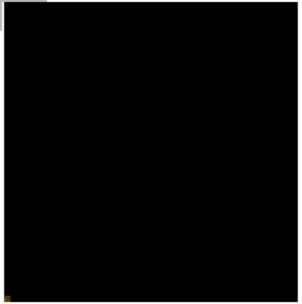


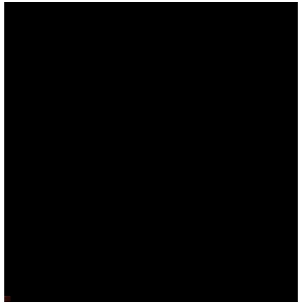
Spectroscopy

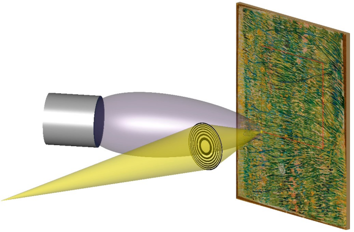
- Spectroscopic methods: measure the response of a system as a function of energy
- The energy that is scanned may be that of the incidient beam (photon, electron, neutron,..) or the energy of the outgoing particles (photons in X-rax fluorescence, electrons in X-ray photo electron spectroscopy)
- Often combined with spatial resolution (imaging): Microspectroscopies and spectromicrsocopies

Microspectroscopies and spectromicroscopies

Microspectroscopies: record energy spectra by scanning a focused incident beam over the sample



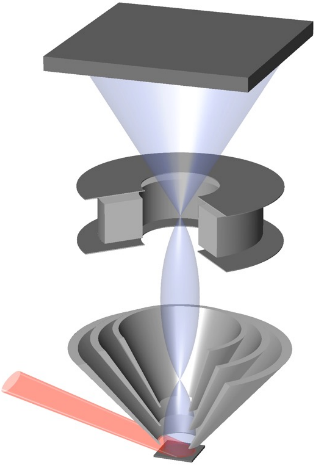


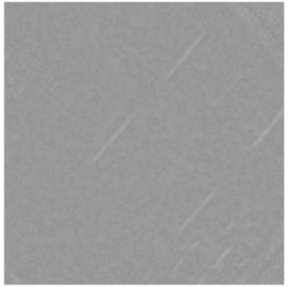


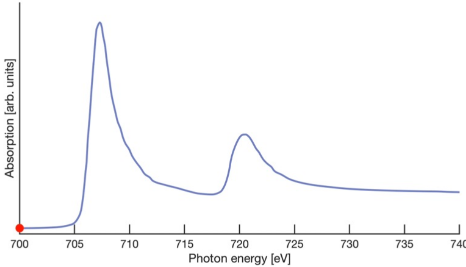
Scanning XRF

J. Dik *et al.*, Anal. Chem. **80** (2008) 6436

Spectromicroscopies: changes of a full-field image as a function of polarization or energy







Photoemission electron microscopy

A. Fraile Rodríguez *et al.*,
J. Phys. D **43** (2010) 474006

Overview of spectroscopy techniques

Technique	Abbreviation	Applications
X-ray absorption near-edge spectroscopy	XANES	Local chemistry, absorbate structure/orientation, oxidation state, coordination, spin state
Photoemission electron microscopy	PEEM	Magnetic structures (ferro-, ferri-, antiferromagnetisms). Variant of XANES
Scanning transmission x-ray microscopy	STXM	Polymer physics, thin films, segregation, morphology. Variant of XANES
Extended x-ray absorption fine structure	EXAFS	Local structure in disordered ("real") systems, trace element detection, chemical dynamics, catalysis
X-ray fluorescence	XRF	Geochemistry, archaeology, forensic science, cultural artifacts/heritage, biology
Resonant inelastic x-ray scattering	RIXS	Electronic structure (charge, orbital, spin), materials science
Angle-resolved photoelectron spectroscopy *(also consider the direction of incoming and outgoing beam)*	ARPES	Electronic structure, surface and interface science
X-ray photoelectron spectroscopy *(measurements of directly ejected electrons, information of core or valence state from which the electrons orginated)*	XPS	Chemistry, surface/absorbate structure, interface chemistry

Variations of XAS

not covered in this course

XAS vs. XPS

- **X-ray absorption spectroscopies (XAS**) are concerned with the change in response of a system as a function of the incident photon energy and as such can only be performed at synchrotrons. In general, an electron is excited to either an unoccupied, bound, valence state, or is completely ejected from the electrostatic influence of its parent atom. This state can then relax via emission of a photon, be scattered elastically or inelastically by neighbouring atoms, or may be radiationless, leading to the ejection of photoelectrons, Auger electrons, and a cascade of low-energy secondary electrons. As such, x-ray absorption spectroscopies probe the unoccupied density of states of the system
- In contrast, **x-ray photoelectron spectroscopies (XPS**) involve the collection and measurement of the energies of directly ejected electrons, yielding information about the core or valence state from which the electrons originated.

Overview of spectroscopy techniques

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Resonant inelastic x-ray scattering	RIXS	not covered in this course	Electronic structure (charge, orbital, spin), materials science
Angle-resolved photoelectron spectroscopy *(also consider the direction of incoming and outgoing beam)*	ARPES		Electronic structure, surface and interface science
X-ray photoelectron spectroscopy *(measurements of directly ejected electrons, information of core or valence state from which the electrons originated)*	XPS		Chemistry, surface/absorbate structure, interface chemistry

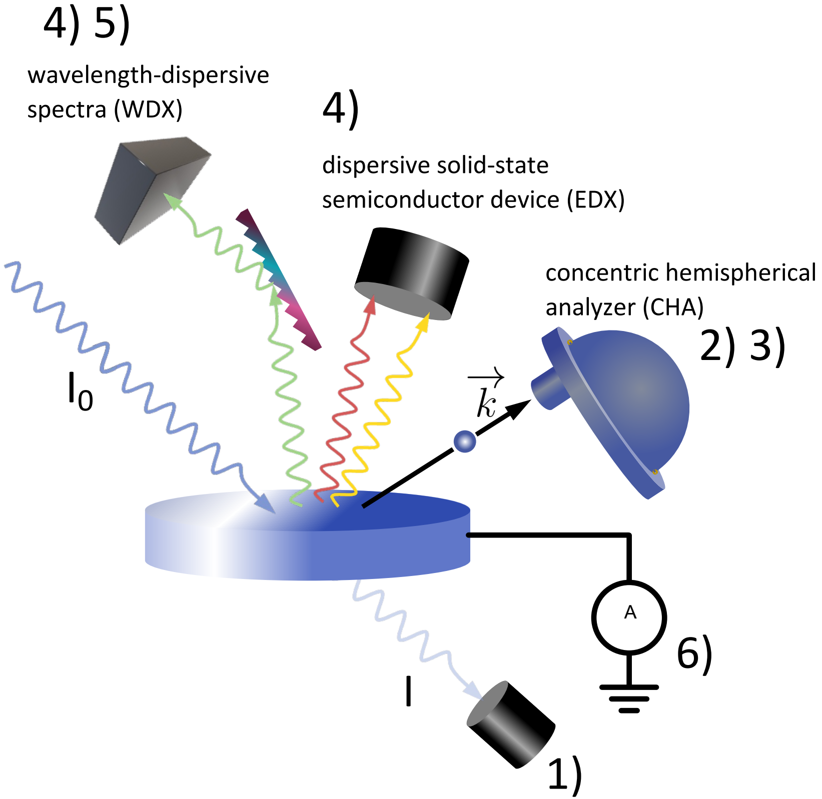
Overview of spectroscopy techniques

Technique	Abbreviation		Scanned $h\nu_{in}$?
X-ray absorption near-edge spectroscopy	XANES	Variations of XAS	✓
Photoemission electron microscopy	PEEM		✓
Scanning transmission x-ray microscopy	STXM		✓
Extended x-ray absorption fine structure	EXAFS		✓
X-ray fluorescence	XRF		
Resonant inelastic x-ray scattering	RIXS	not covered in this course	✓
Angle-resolved photoelectron spectroscopy	ARPES		(✓)
X-ray photoelectron spectroscopy	XPS		(✓)

scanning the incident photon energy → only possible at synchrotrons!

XRF use a constant incident photon energy → can also be performed on a lab source

Detection methods



Form of detection

1) Transmitted x-radiation
2) Emitted photoelectrons
   Also as function of $\vec{k}$
3) Auger electrons
4) Emitted fluorescence
5) Inelastically scattered x-radiation

Spectrally resolved

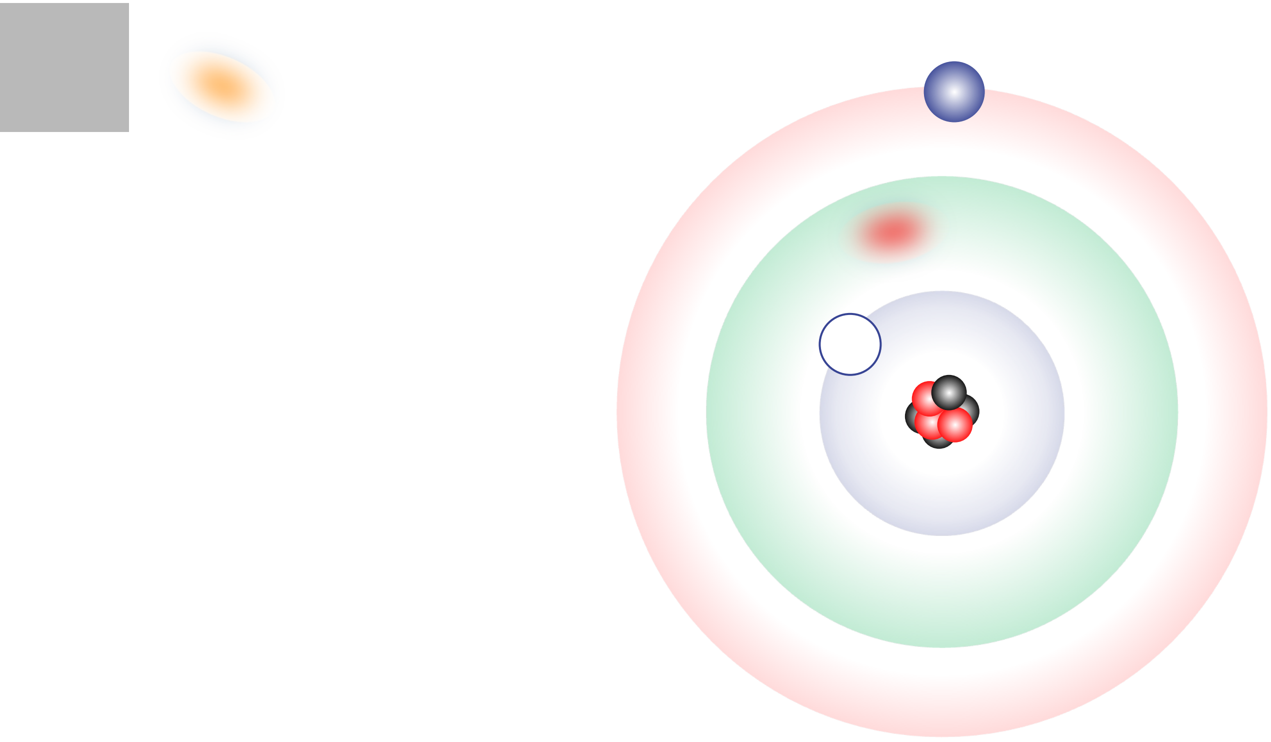
6) Secondary electrons/total electron yield
   - Not spectrally resolved
   - Used as a measure of absorption strength

Philip Willmott: Synchrotron and X-ray Free Electron Laser

Overview of spectroscopy techniques

Technique	Abbreviation		Scanned $h\nu_{in}$?	Detection methods
X-ray absorption near-edge spectroscopy	XANES	Variations of XAS	✓	1, 2, 4, 6
Photoemission electron microscopy	PEEM		✓	6
Scanning transmission x-ray microscopy	STXM		✓	1, 3
Extended x-ray absorption fine structure	EXAFS		✓	1, 2, 4, 6
X-ray fluorescence	XRF			4
Resonant inelastic x-ray scattering	RIXS	not covered in this course	✓	5
Angle-resolved photoelectron spectroscopy	ARPES		(✓)	2
X-ray photoelectron spectroscopy	XPS		(✓)	2, 3

Photoelectrons and fluorescence



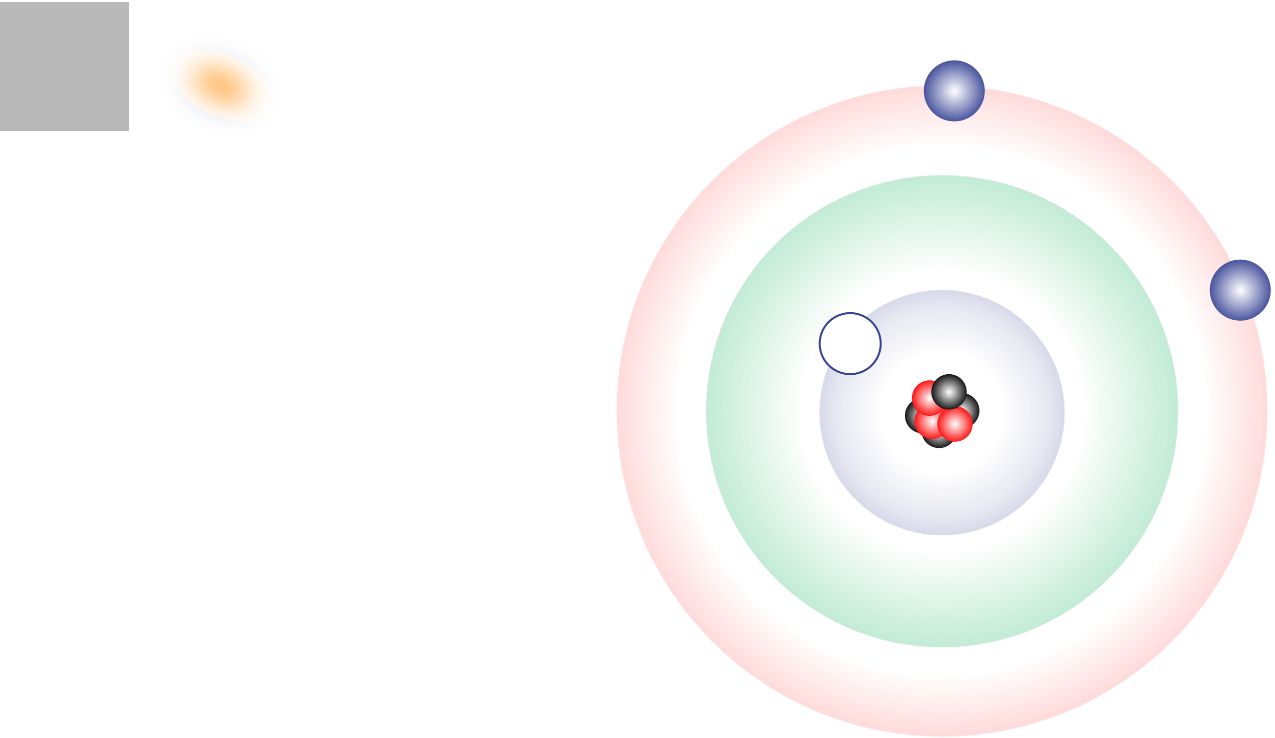
Photoelectron

$$KE = h\nu_{in} - E_B$$

$$h\nu_{in} > h\nu_{out}$$

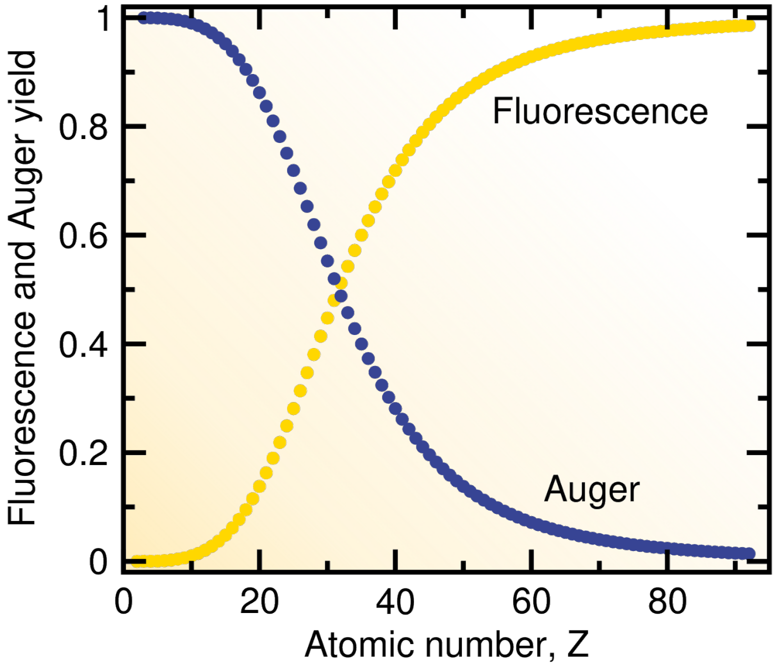
$$h\nu_{out} = E_{B,1} – E_{B,2}$$

Auger electrons



Auger-electron
KE independent of hν

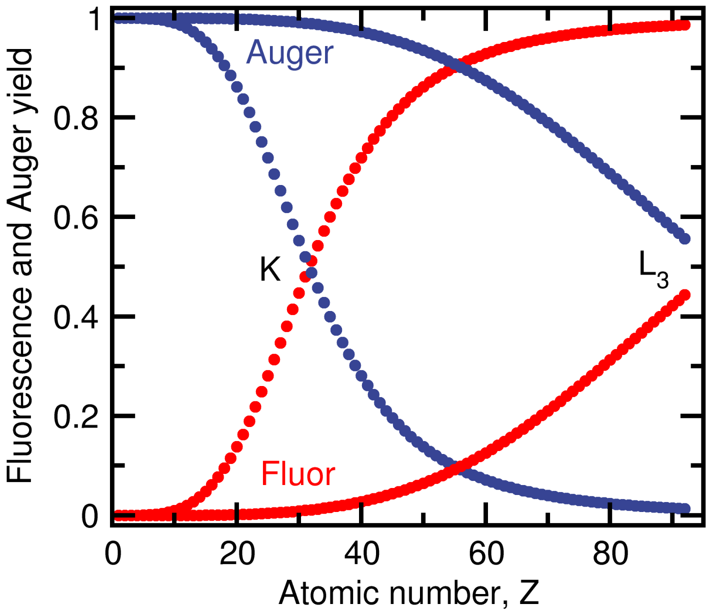
Fluorescence or Auger?



$$p_{\text{fl}} \propto (h\nu)^3$$

$$Y_K = \frac{Z^4}{10^6 + Z^4}$$

Fluorescence or Auger?



Fluorescence

Spontaneous process, determined by "Einstein-A coefficient" A_{21}

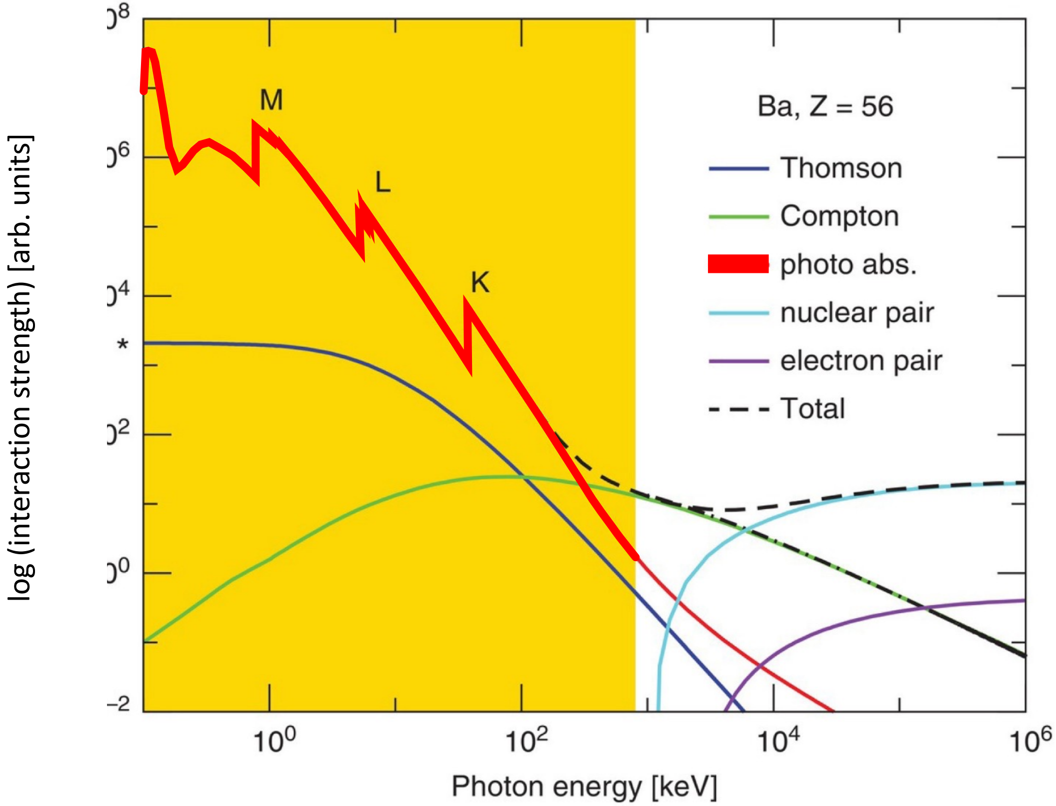
$A_{21} \propto hn^3$

Dominates for relaxation to empty K-states in high-Z elements

$$Y_{K,L_3} = \frac{Z^4}{A_{K,L_3} + Z^4}$$

$A_K \approx 10^6$ $\qquad A_{L_3} \approx 9 \times 10^7$

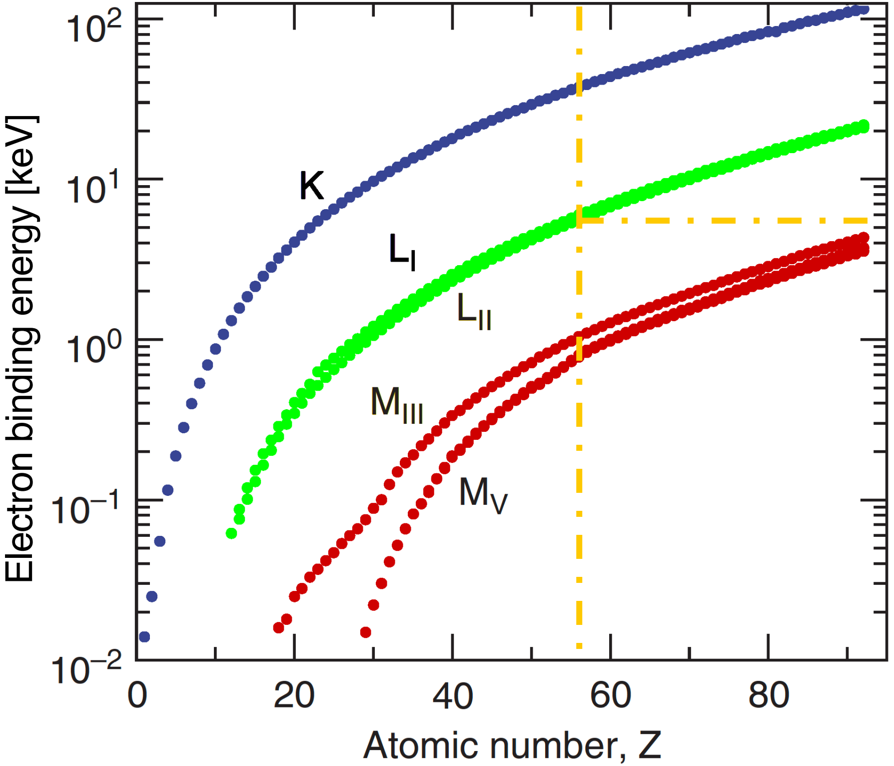
Interaction strengths of photo absorption

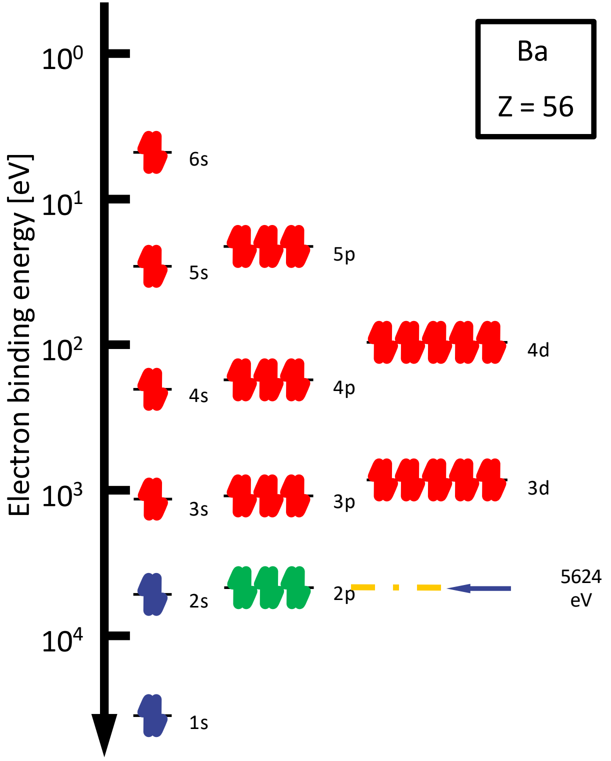


absorption cross-section varies approximitely as the third power of the photon energy, interrupted by step-like increases in absorption as the photon energy matches the ionization potential of an occupied electron state in the atom.

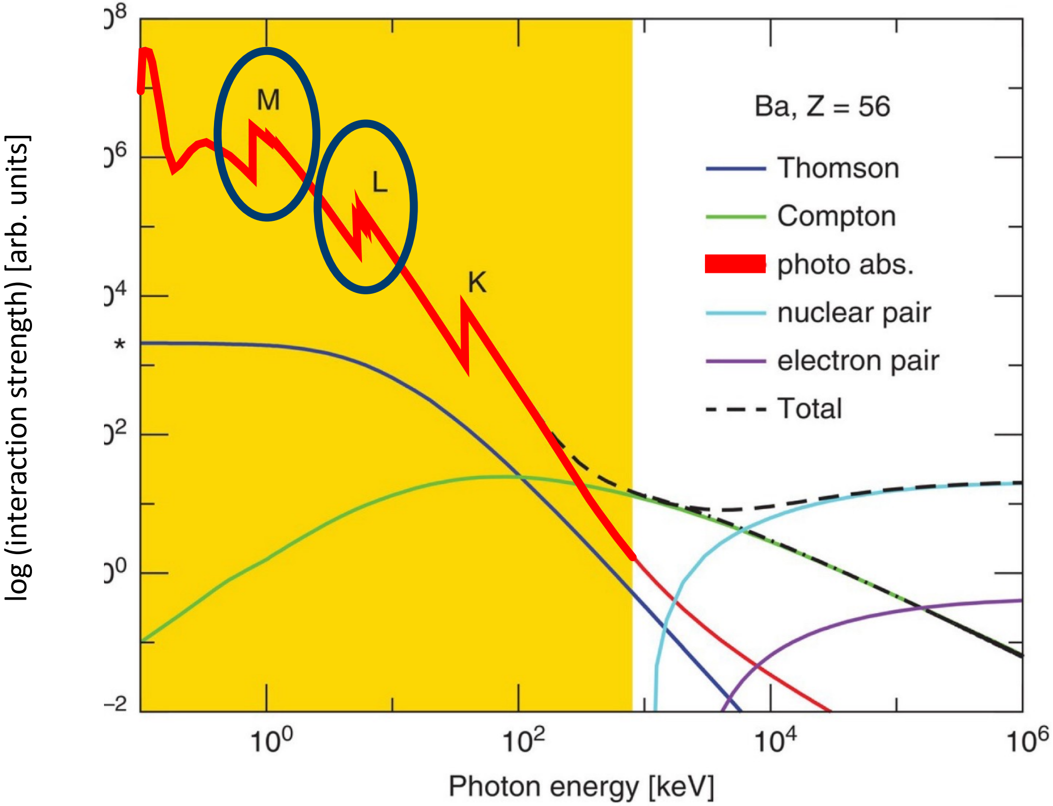
Philip Willmott: Synchrotron and X-ray Free Electron Laser

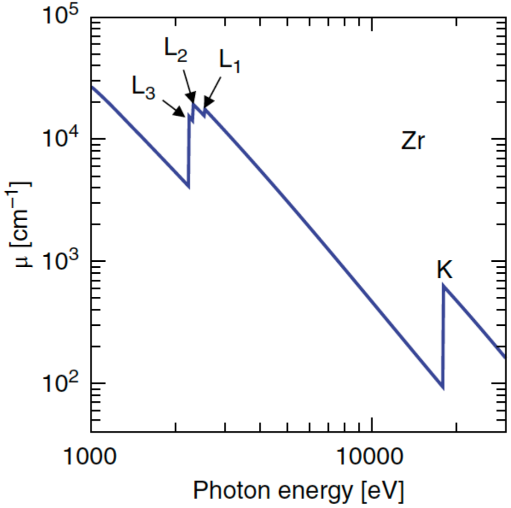
Electron binding energies of the elements





Interaction strengths of x-rays with matter





all absorption edges except the K-edges exhibit three or more more “sub-edges”

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X-ray fluorescence emission lines

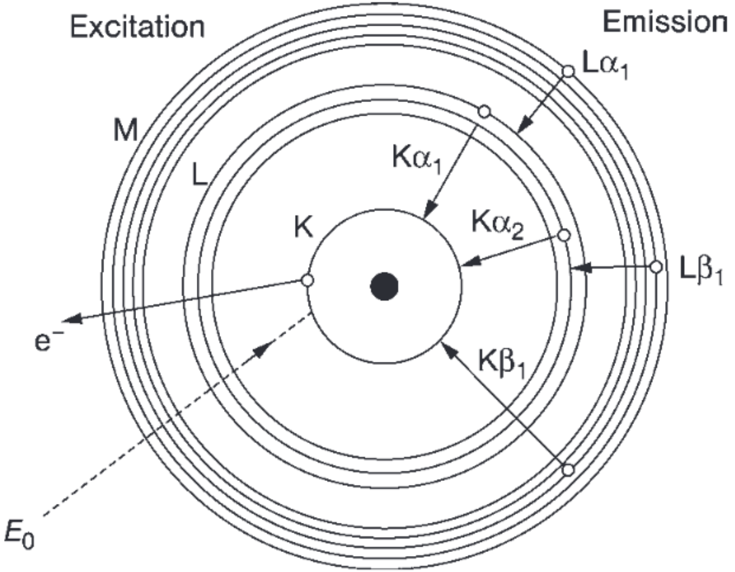


Figure 1. Scheme of X-ray fluorescence: an electron in the K shell is ejected from the atom by an incident photon of energy E_0 (dashed line). The vacancy is filled by an electron from the L shell and K X rays are emitted, in competition with Auger electrons

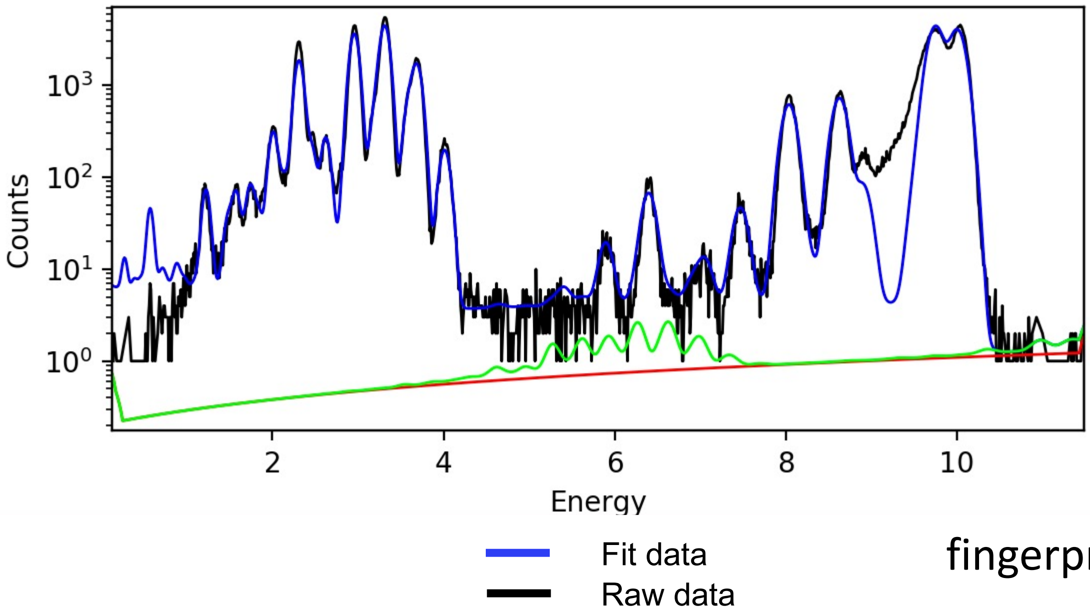
Fitton, G. (2014). X-ray fluorescence spectrometry., 87–115. https://doi.org/10.1007/978-3-030-58292-0_240014

Theoretically, when K shells are excited, four lines are emitted by each element: $K_{\alpha1}$, $K_{\alpha2}$, $K_{\beta1}$, and $K_{\beta2}$. When L shells are excited, nine lines are emitted by each element, i.e., $L_{\alpha1}$, $L_{\alpha2}$, $L_{\beta1}$, $L_{\beta2}$, $L_{\beta3}$, $L_{\gamma1}$, $L_{\gamma3}$, L_{λ}, and L_{η}. When M-shells are excited, four lines are emitted, i.e. $M_{\alpha1}$, $M_{\alpha2}$, M_{β}, and M_{γ}.

From a **practical point** of view, and because of the finite energy the line combinations $L_{\alpha1}$ –$L_{\alpha2}$ and $L_{\beta1}$ –$L_{\beta2}$ –$L_{\beta3}$ approximately coincide in a unique larger peak, and the same happens for the pairs $K_{\alpha1}$ –$K_{\alpha2}$ and $K_{\beta1}$ –$K_{\beta2}$, at least for elements with atomic number up to about Z =50. The K lines are therefore identified by two lines **K_{α} and K_{β}**, and L lines by six lines **L_{α}, L_{β},** $L_{\gamma1}$, $L_{\gamma3}$, L_{λ}, and L_{η}, of which only the first two are of high intensity.
$M_{\alpha1}$, $M_{\alpha2}$, M_{β}, and M_{γ} always coincide in an unique peak, and M lines, detected as a single line, are in any case only visible for heavy elements.

X-ray fluorescence (XRF)

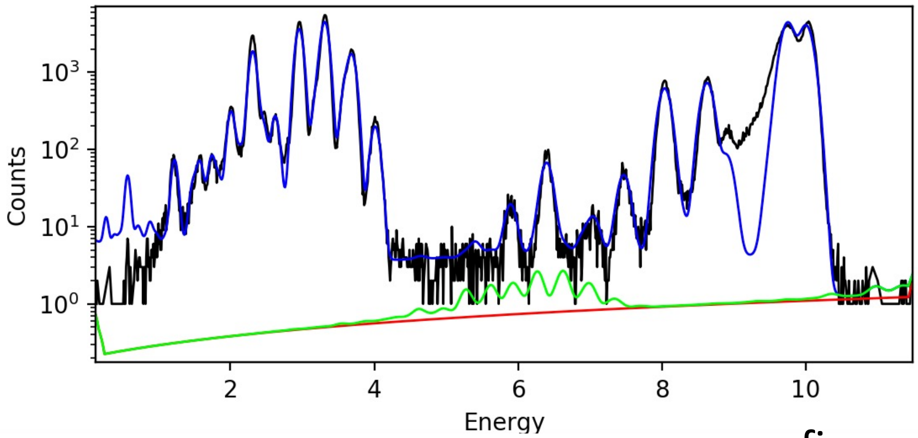
X-ray fluorescence spectrum (measured with 10 keV X-rays)



fingerprint of elements

X-ray fluorescence spectrum

- **A set of X lines for each detectable element present in the analyzed object (in the form of K and/or L and/or M X rays; energy and intensity of these lines depend on the composition of the object).**



fingerprint of elements

Periodic Table of Elements and X-ray Energies

www.bruker.com/hhxrf

Atomic number	Symbol	Element name	Atomic weight	Density (g/cm³)	Spectral line	Energy (keV)	Spectral line	Energy (keV)
1	H	Hydrogen	1.01	0.0007				
2	He	Helium	4.00	0.0002				
3	Li	Lithium	6.94	0.53				
4	Be	Beryllium	9.01	1.85	Kα	0.108		
5	B	Boron	10.81	2.34	Kα	0.183		
6	C	Carbon	12.01	2.27	Kα	0.277		
7	N	Nitrogen	14.01	0.001	Kα	0.392		
8	O	Oxygen	16.00	0.001	Kα	0.525		
9	F	Fluorine	19.00	0.001	Kα	0.677		
10	Ne	Neon	20.18	0.0009	Kα	0.849		
11	Na	Sodium	22.99	0.97	Kα	1.040		
12	Mg	Magnesium	24.31	1.74	Kα	1.254		
13	Al	Aluminium	26.98	2.70	Kα	1.486		
14	Si	Silicon	28.09	2.33	Kα	1.740		
15	P	Phosphorus	30.97	1.82	Kα	2.010		
16	S	Sulfur	32.07	2.07	Kα	2.309		
17	Cl	Chlorine	35.45	0.003	Kα	2.622		
18	Ar	Argon	39.95	0.002	Kα	2.958		
19	K	Potassium	39.10	0.86	Kα	3.314		
20	Ca	Calcium	40.08	1.54	Kα	3.692	Lα	0.341
21	Sc	Scandium	44.96	2.99	Kα	4.093	Lα	0.395
22	Ti	Titanium	47.87	4.54	Kα	4.512	Lα	0.452
23	V	Vanadium	50.94	6.11	Kα	4.953	Lα	0.510
24	Cr	Chromium	52.00	7.15	Kα	5.415	Lα	0.572
25	Mn	Manganese	54.94	7.44	Kα	5.900	Lα	0.637
26	Fe	Iron	55.85	7.87	Kα	6.405	Lα	0.705
27	Co	Cobalt	58.93	8.86	Kα	6.931	Lα	0.775
28	Ni	Nickel	58.69	8.91	Kα	7.480	Lα	0.849
29	Cu	Copper	63.55	8.93	Kα	8.046	Lα	0.928
30	Zn	Zinc	65.38	7.13	Kα	8.637	Lα	1.012
31	Ga	Gallium	69.72	5.91	Kα	9.251	Lα	1.098
32	Ge	Germanium	72.64	5.32	Kα	9.886	Lα	1.188
33	As	Arsenic	74.92	5.78	Kα	10.543	Lα	1.282
34	Se	Selenium	78.96	4.81	Kα	11.224	Lα	1.379
35	Br	Bromine	79.90	3.12	Kα	11.924	Lα	1.481
36	Kr	Krypton	83.80	0.004	Kα	12.648	Lα	1.585
37	Rb	Rubidium	85.47	1.53	Kα	13.396	Lα	1.692
38	Sr	Strontium	87.62	2.64	Kα	14.165	Lα	1.806
39	Y	Yttrium	88.91	4.47	Kα	14.958	Lα	1.924
40	Zr	Zirconium	91.22	6.51	Kα	15.775	Lα	2.044
41	Nb	Niobium	92.91	8.57	Kα	16.615	Lα	2.169
42	Mo	Molybdenum	95.94	10.22	Kα	17.480	Lα	2.292
43	Tc	Technetium	(98)	11.50	Kα	18.367	Lα	2.423
44	Ru	Ruthenium	101.07	12.37	Kα	19.279	Lα	2.558
45	Rh	Rhodium	102.91	12.41	Kα	20.216	Lα	2.697
46	Pd	Palladium	106.42	12.02	Kα	21.177	Lα	2.838
47	Ag	Silver	107.87	10.50	Kα	22.163	Lα	2.983
48	Cd	Cadmium	112.41	8.69	Kα	23.173	Lα	3.133
49	In	Indium	114.82	7.31	Kα	24.210	Lα	3.286
50	Sn	Tin	118.71	7.29	Kα	25.271	Lα	3.444
51	Sb	Antimony	121.76	6.69	Kα	26.359	Lα	3.604
52	Te	Tellurium	127.60	6.23	Kα	27.473	Lα	3.768
53	I	Iodine	126.90	4.93	Kα	28.612	Lα	3.938
54	Xe	Xenon	131.29	0.006	Kα	29.775	Lα	4.110
55	Cs	Cesium	132.91	1.87	Kα	30.973	Lα	4.285
56	Ba	Barium	137.33	3.59	Kα	32.194	Lα	4.466
57	La	Lanthanum	138.91	6.15	Kα	33.442	Lα	4.647
58	Ce	Cerium	140.12	6.77	Lα	4.839	Mα	0.884
59	Pr	Praseodymium	140.91	6.77	Lα	5.035	Mα	0.927
60	Nd	Neodymium	144.24	7.01	Lα	5.228	Mα	0.979
61	Pm	Promethium	(145)	7.26	Lα	5.432	Mα	1.023
62	Sm	Samarium	150.36	7.52	Lα	5.633	Mα	1.078
63	Eu	Europium	151.96	5.24	Lα	5.849	Mα	1.131
64	Gd	Gadolinium	157.25	7.90	Lα	6.053	Mα	1.181
65	Tb	Terbium	158.93	8.23	Lα	6.273	Mα	1.240
66	Dy	Dysprosium	162.50	8.55	Lα	6.498	Mα	1.293
67	Ho	Holmium	164.93	8.80	Lα	6.720	Mα	1.348
68	Er	Erbium	167.26	9.07	Lα	6.949	Mα	1.404
69	Tm	Thulium	168.93	9.32	Lα	7.180	Mα	1.462
70	Yb	Ytterbium	173.04	6.97	Lα	7.416	Mα	1.526
71	Lu	Lutetium	174.47	9.84	Lα	7.655	Mα	1.580
72	Hf	Hafnium	178.49	13.31	Lα	7.899	Mα	1.646
73	Ta	Tantalum	180.95	16.65	Lα	8.146	Mα	1.712
74	W	Tungsten	183.84	19.25	Lα	8.398	Mα	1.775
75	Re	Rhenium	186.21	21.02	Lα	8.652	Mα	1.843
76	Os	Osmium	190.23	22.61	Lα	8.911	Mα	1.907
77	Ir	Iridium	192.22	22.65	Lα	9.175	Mα	1.980
78	Pt	Platinum	195.08	21.46	Lα	9.442	Mα	2.050
79	Au	Gold	196.97	19.28	Lα	9.713	Mα	2.123
80	Hg	Mercury	200.59	13.53	Lα	9.989	Mα	2.195
81	Tl	Thallium	204.37	11.85	Lα	10.269	Mα	2.271
82	Pb	Lead	207.20	11.34	Lα	10.551	Mα	2.342
83	Bi	Bismuth	208.98	9.81	Lα	10.839	Mα	2.423
84	Po	Polonium	(209)	9.32	Lα	11.131	Mα	2.499
85	At	Astatine	(210)	7.00	Lα	11.427	Mα	2.577
86	Rn	Radon	(222)	0.01	Lα	11.727	Mα	2.654
87	Fr	Francium	(223)	1.87	Lα	12.031	Mα	2.732
88	Ra	Radium	(226)	5.50	Lα	12.339	Mα	2.806
89	Ac	Actinium	(227)	10.07	Lα	12.652	Mα	2.900
90	Th	Thorium	232.04	11.72	Lα	12.968	Mα	2.996
91	Pa	Protactinium	231.04	15.37	Lα	13.291	Mα	3.082
92	U	Uranium	238.03	18.95	Lα	13.614	Mα	3.171
93	Np	Neptunium	(237)	20.45	Lα	13.946	Mα	3.250
94	Pu	Plutonium	(244)	19.84	Lα	14.282	Mα	3.339
95	Am	Americium	(243)	13.69	Lα	14.620	Mα	3.438
96	Cm	Curium	(247)	13.51				
97	Bk	Berkelium	(247)	14.79				
98	Cf	Californium	(251)	15.1				
99	Es	Einsteinium	(252)	13.5				
100	Fm	Fermium	(257)					
101	Md	Mendelevium	(258)					
102	No	Nobelium	(259)					
103	Lr	Lawrencium	(262)					

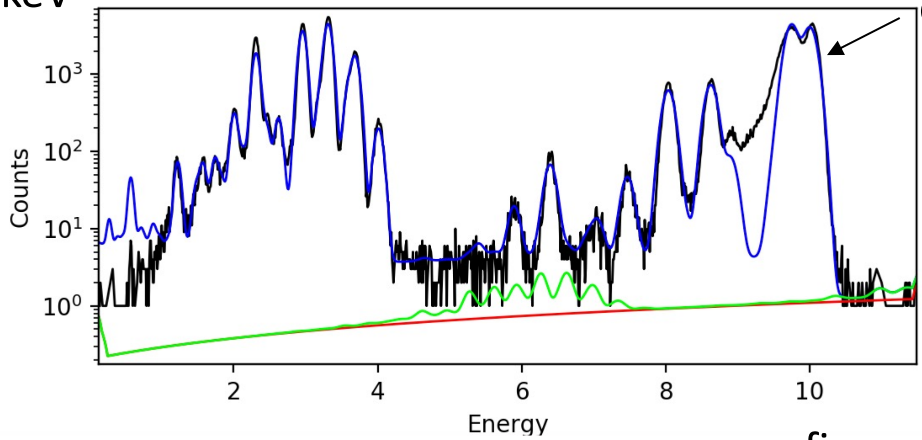
Atomic number
35 79.90 — Atomic weight
Br 3.12 — Density (g/cm³)
Symbol
Bromine — Element name
Kα 11.924
Lα 1.481 — Energy (keV)
Spectral line

X-ray fluorescence spectrum

- **A set of X lines for each detectable element present in the analyzed object (in the form of K and/or L and/or M X rays; energy and intensity of these lines depend on the composition of the object).**
- A continuous contribution due to Compton and elastic scattering of incident radiation (depending on the excitation source and on the sample).

measured with 10keV

elastic scattering

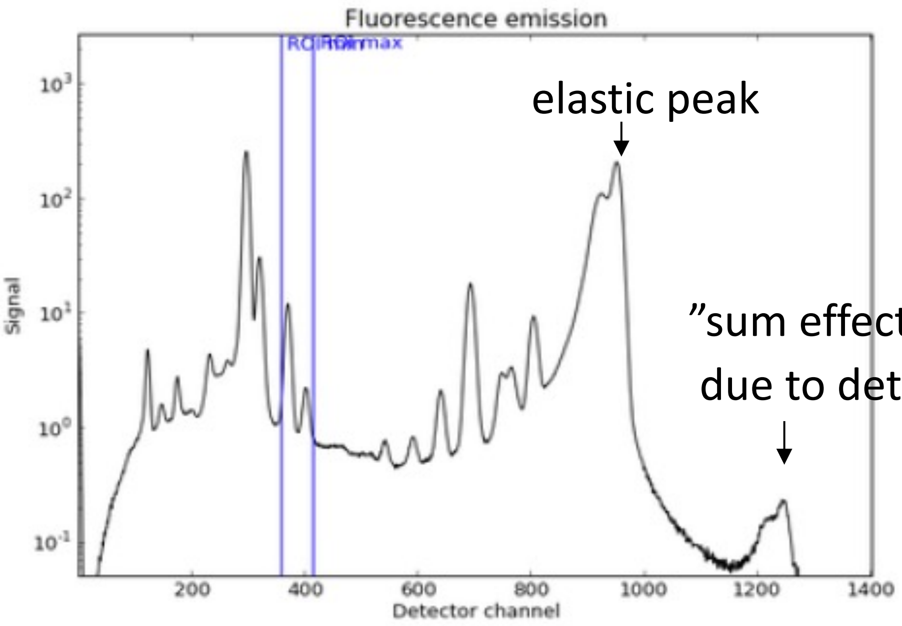


fingerprint of elements

X-ray fluorescence spectrum

- **A set of X lines for each detectable element present in the analyzed object (in the form of K and/or L and/or M X rays; energy and intensity of these lines depend on the composition of the object).**
- A continuous contribution due to Compton and elastic scattering of incident radiation (depending on the excitation source and on the sample).
- Lines due to possible ‘‘escape’’ of incident lines in the detector (photoelectric effect of photon in the detector)
- Lines due to possible ‘‘sum’’ effects in the detector (two photons proscessed within the resolution time).
- Possible lines due to elements in some way irradiated by incident and/or secondary radiation present, for example, in the source shielding or in the source and/or detector collimators and filters.
- Argon K-X line due to photoelectric effect in air (ca. 0.9% argon).

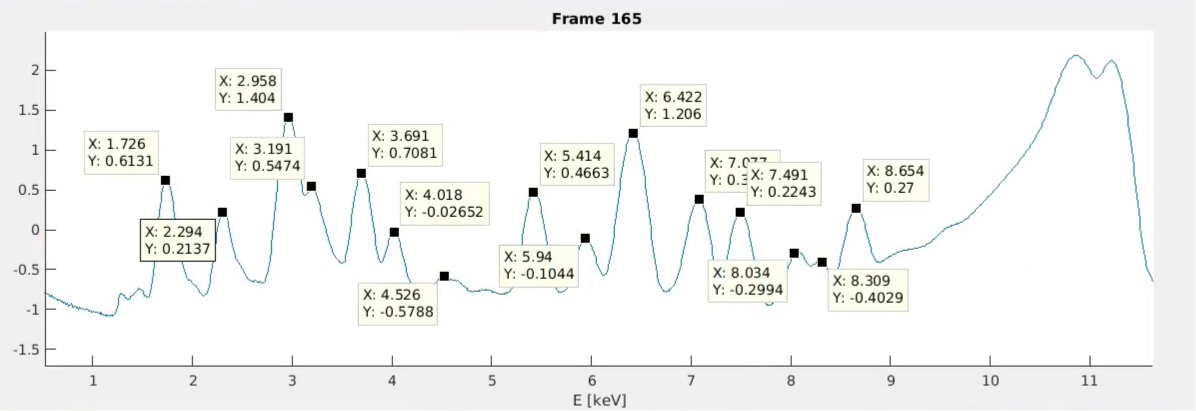
X-ray fluorescence (XRF)



elastic peak

"sum effect" or "pile-up" due to detector saturation

XRF: a first qualitative analysis



1.7 : Si, embedding material or detector?

2.3: S

2.95 Ar from air

3.2 Ar from air

3.69 & 4 Ca

4.5 very weak

5.4& 5.94 Cr

6.4 7.05 Fe

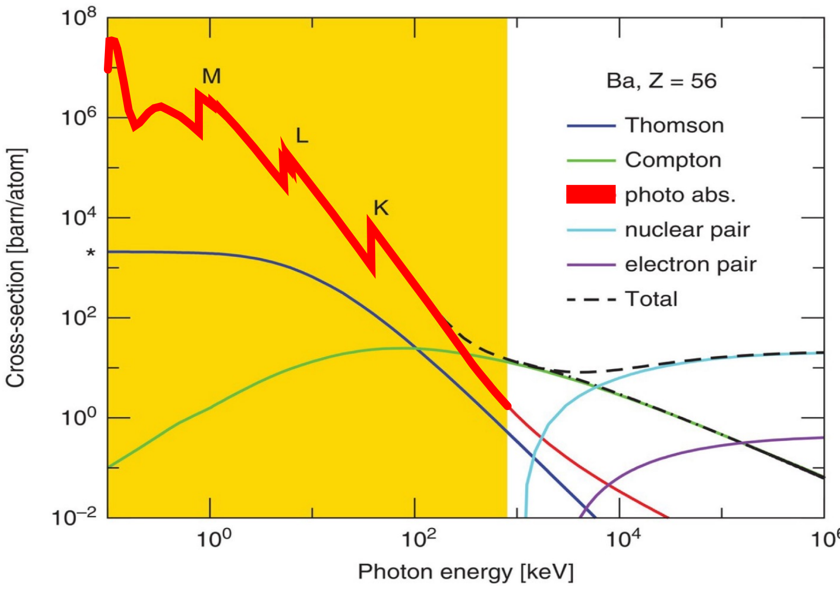
7.49 Ni

8.03 & 8.3 Cu

8.65 Zn

XRF at Labsource vs. Synchrotron

- XRF can be done on lab sources or at synchrotrons
- not monochromatic X-ray beam: adds background noise
- X-ray energy has to be higher than the excitation energy of the probed element
- for a specific element to increase sensitivity: largest cross-section just above the edge



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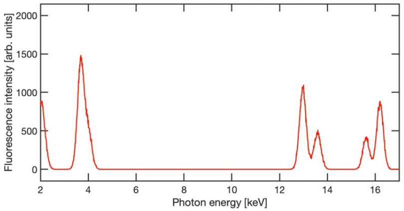
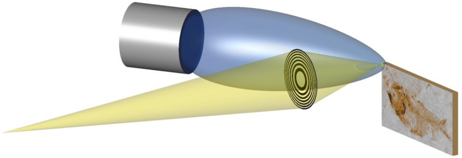
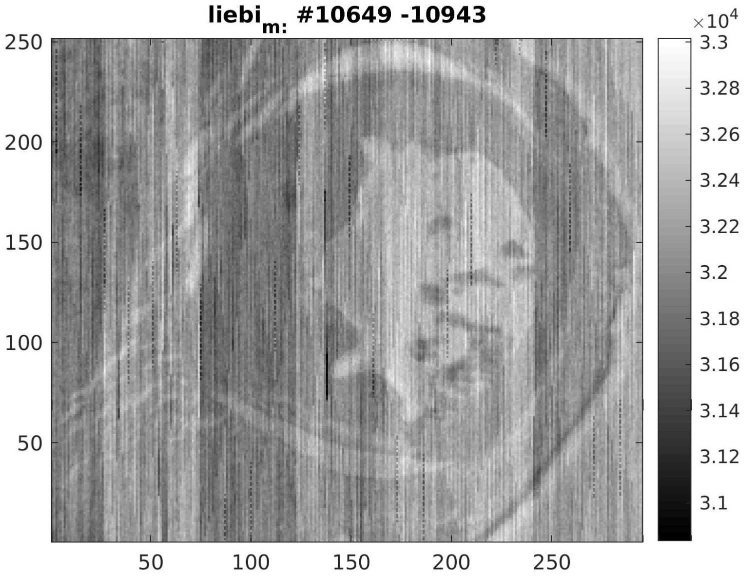
- X-ray energy has to be higher than the excitation energy of the probed element
- for a specific element to increase sensitivity: largest cross-section just above the edge
- high flux and small beam → high spatial resolution and high sensitvity (ppm)



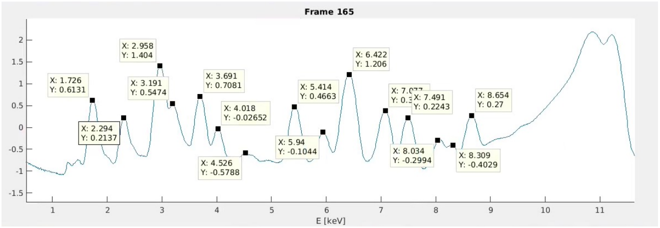


scanning XRF: Microspectroscopy

XRF measurement at cSAXS



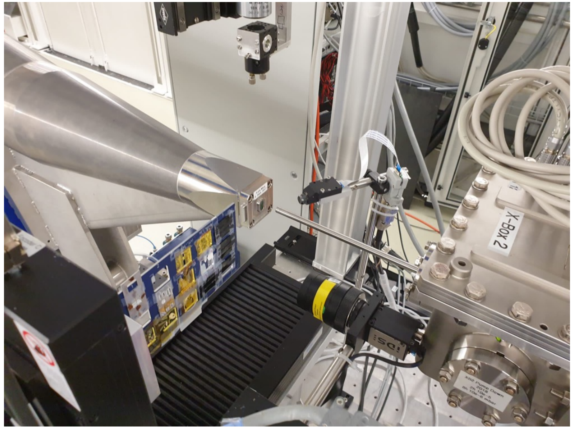
transmission signal (and top-up of SLS!)



thin section of umbilical cord with calcifications measured at cSAXS

12um x 8 um beamsize

11.2 keV



XRF analysis

- PyMCA

developed at ESRF, free to use

Guide/Tutorial and downloads at: http://pymca.sourceforge.net/

more simplified and straight forward guide at NanoMAX webpage:

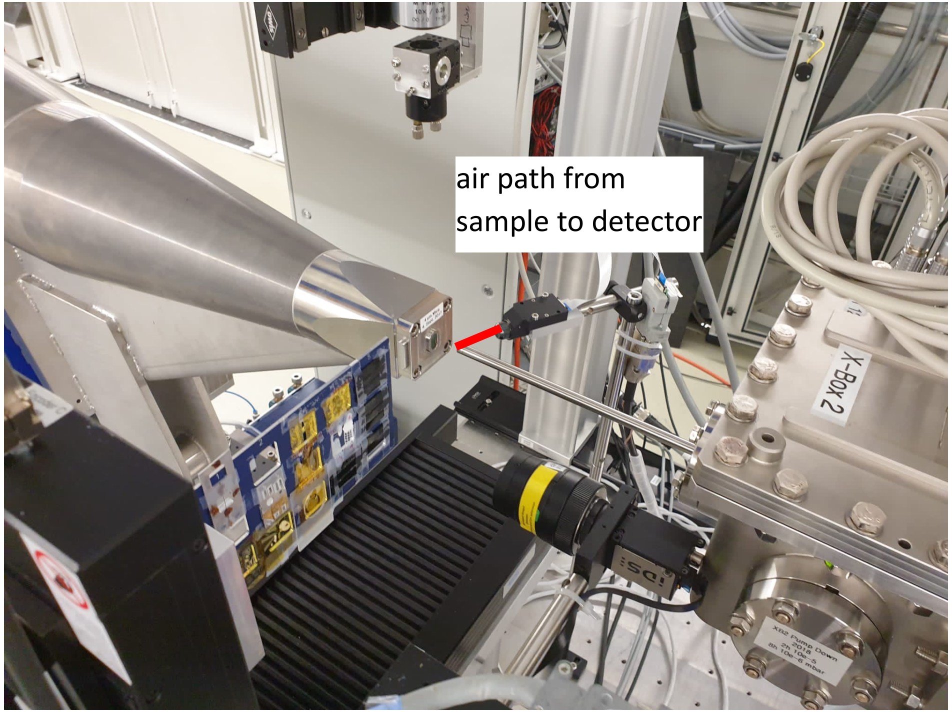
https://www.maxiv.lu.se/beamlines-accelerators/beamlines/nanomax/user-information/experimental-station/data-access-and-processing/

- estimates background and removes escape peaks, sum effects, scattering
- Least-squares fitting of fluorescence peaks (Gaussian)
- Quantifies are under the element specific peaks
  - without standard → mostly qualitative comparison within and between elements
  - with standard → estimation of concentration possible and quantitative comparison between elements (for thin samples)

Quantification

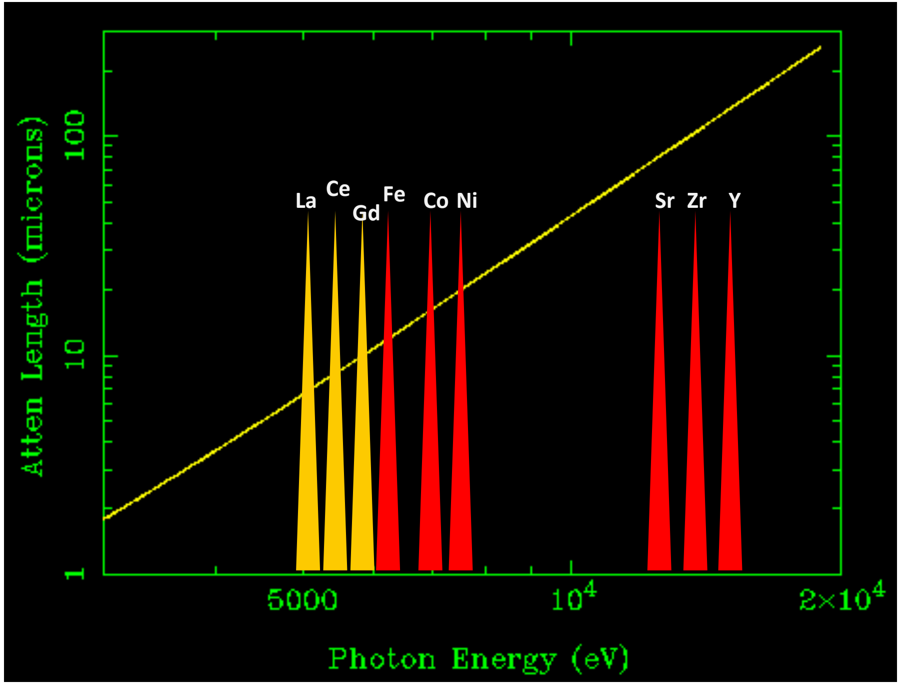
- To analyze samples quantitatively an X-ray fluorescence reference standard is normally used. A typical standard is a thin film sample, where several elements have been deposited on a very thing silicon nitride window.
- for example AXO Dresden: http://www.axo-dresden.de/mainframe_reference.htm
- The calibration measurement must be done with the same conditions as the samples were measured; the same photon energy, incidence angle, exit angle, distance to detector, surrounding of the sample area, etc. Calibration should be measured right before or after the sample measurement.
- Main problem for quantification is self-absorbance, in particular for heterogenous samples

Absorbance in air and self-absorbance



- air path: aborbance of lower-energy lines →measurement in vacuum is beneficial
- self-absorbance within the sample: quantification of thicker samples is very complicated (in particular for hetereogenous samples)
- for lower energies only the last layer probed → different resolution and sensitivity for different elements!

What elements we want to see? What sample size?

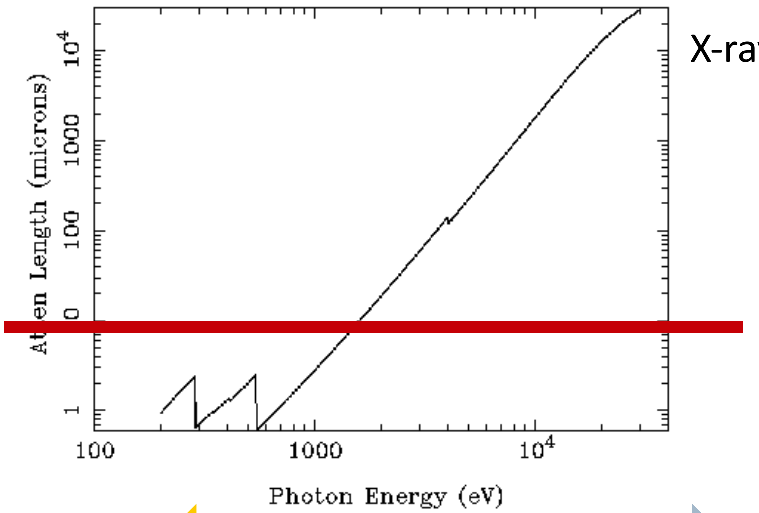


Solid Oxide Fuel/Electrolyzer Cell

Dario Ferreira Sanchez, PSI

https://henke.lbl.gov/optical_constants/atten2.html

X-ray Penetration depth in human body



Skin dead layer
(no health risk)

X-ray penetration depth in human body

Look through thick objects
Medical X-Ray
150 keV

Work in He / Vacuum

Work in air

Thin sample

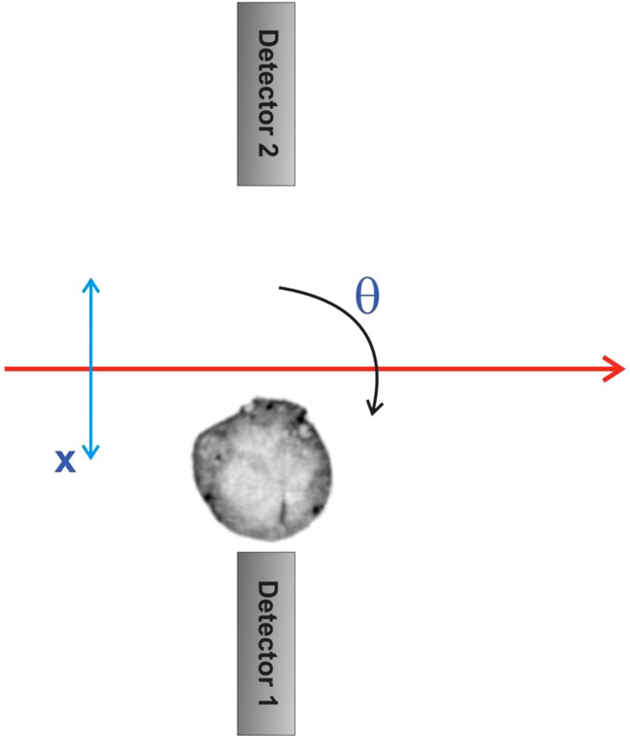
sensitivity to smaller total amounts

Thick sample

More Radiation damage

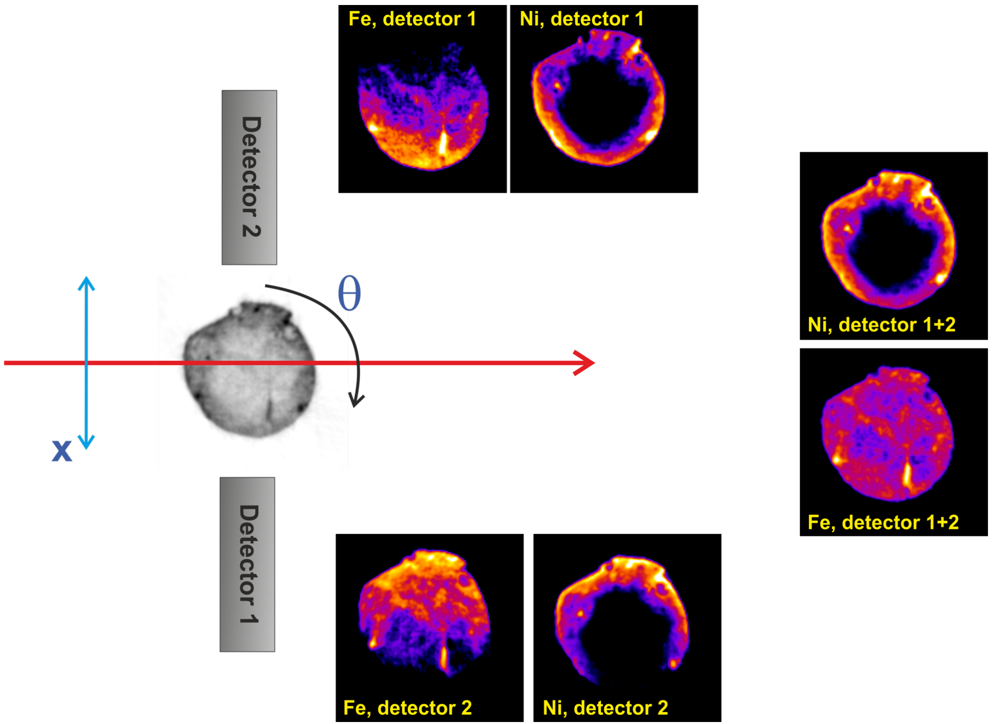
Dose per volume

µXRF scanning tomography



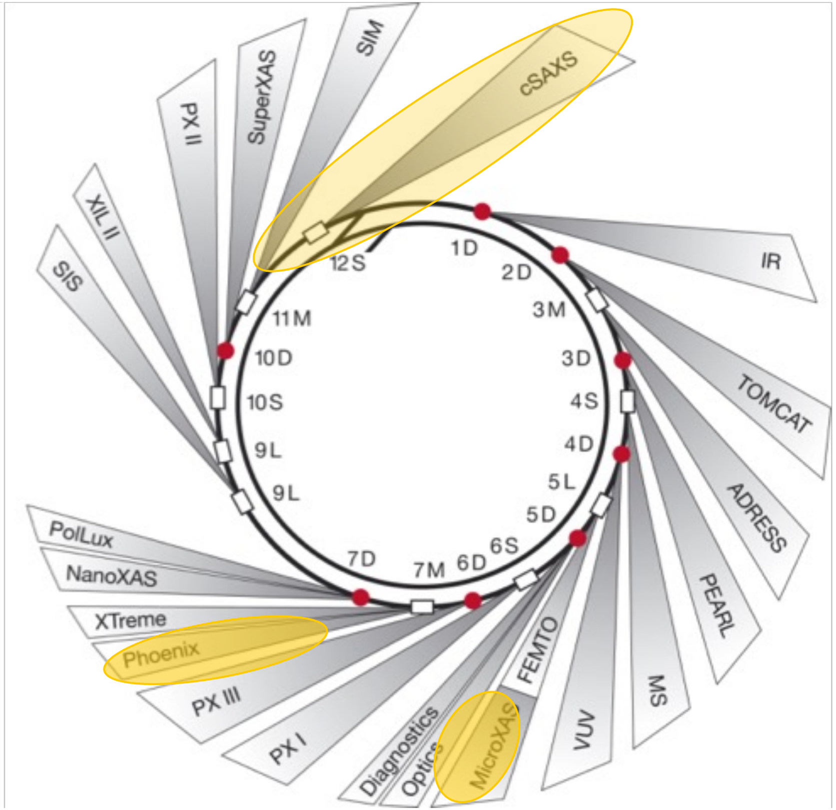
Dario Ferreira Sanchez, PSI

µXRF scanning tomography: self-aborbance



Dario Ferreira Sanchez, PSI

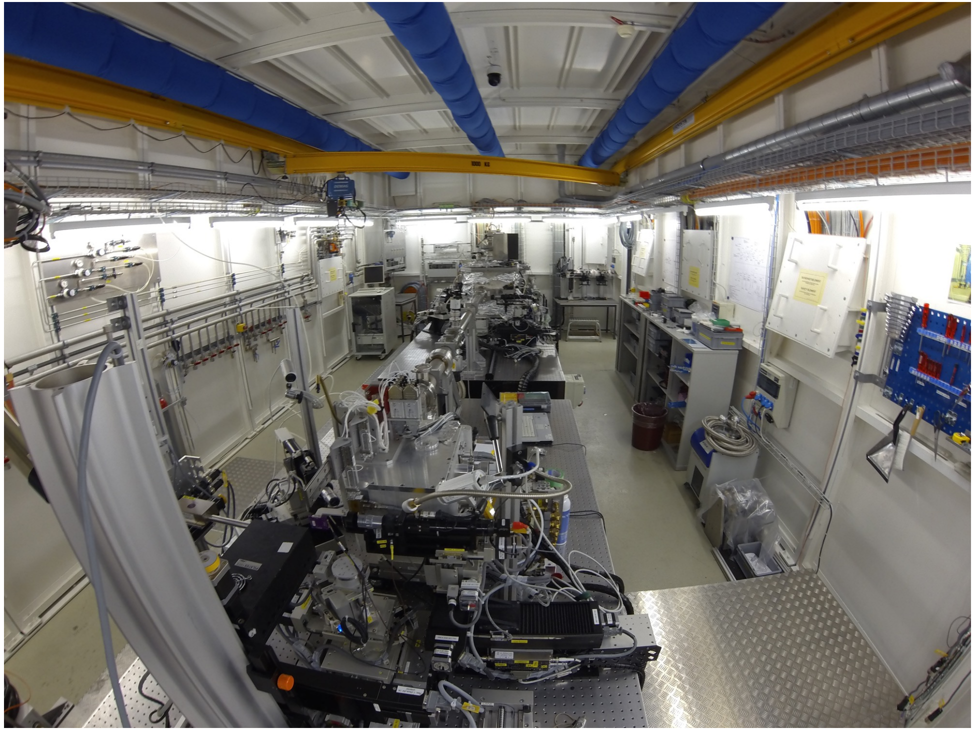
XRF @PSI



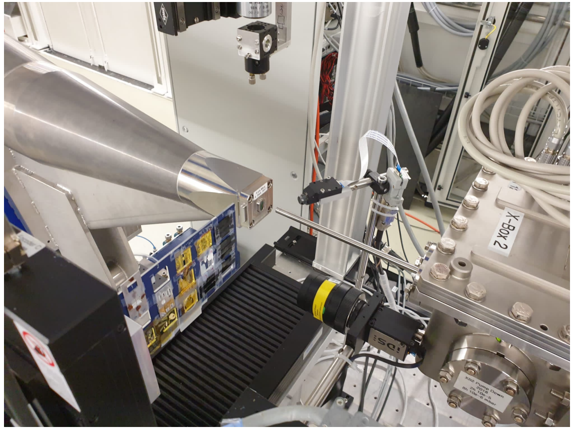
SIM
SuperXAS
PX II
cSAXS
XIL II
SIS
IR
TOMCAT
ADRESS
PEARL
MS
VUV
FEMTO
MicroXAS
Optics
Diagnostics
PX I
PX III
Phoenix
XTreme
NanoXAS
PolLux
1D
2D
3M
3D
4S
4D
5L
5D
6S
6D
7M
7D
9L
9L
10S
10D
11M
12S

SLS beamlines with XRF capabilities

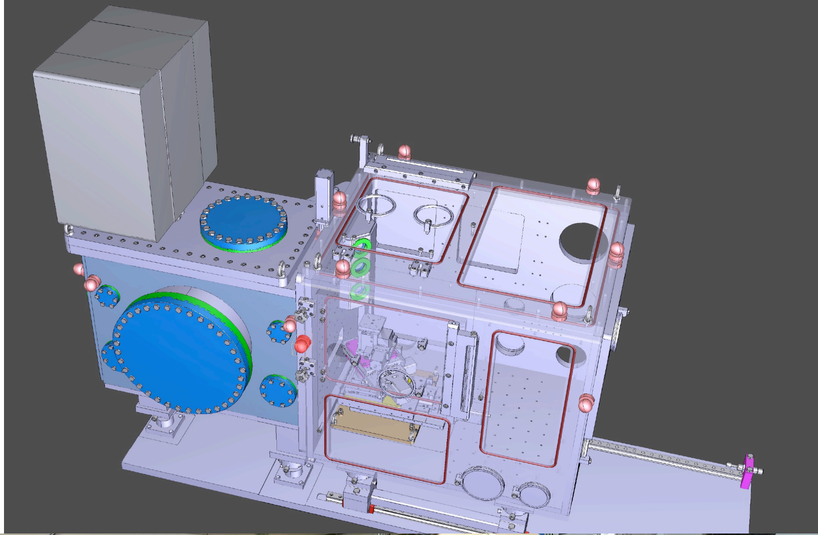
microXAS

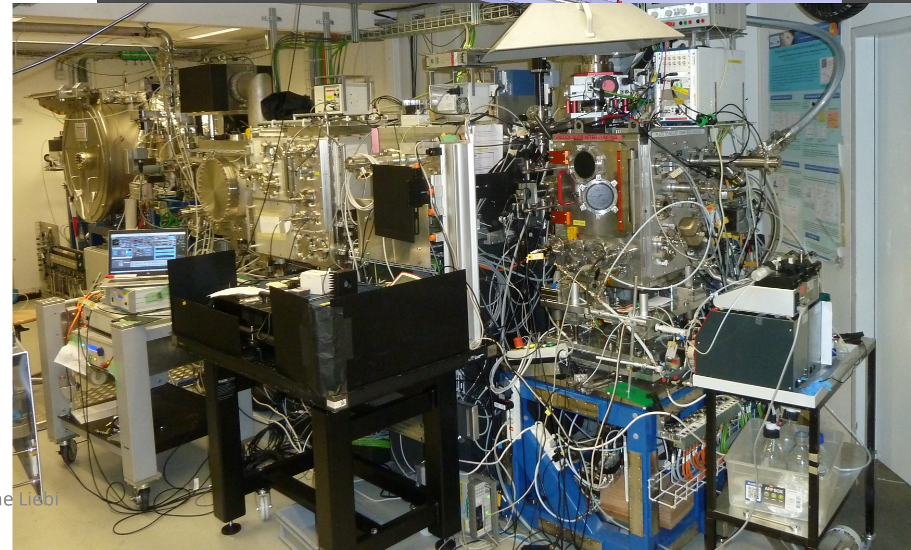


cSAXS



PHOENIX beamline





XAS in tender energy range

PHOENIX I   0.8-8 keV, DCM, microfocus~ 2.5X 2.5 mm

PHOENIX II 0.4-2 keV planar grating, microfocus 4X5 mm

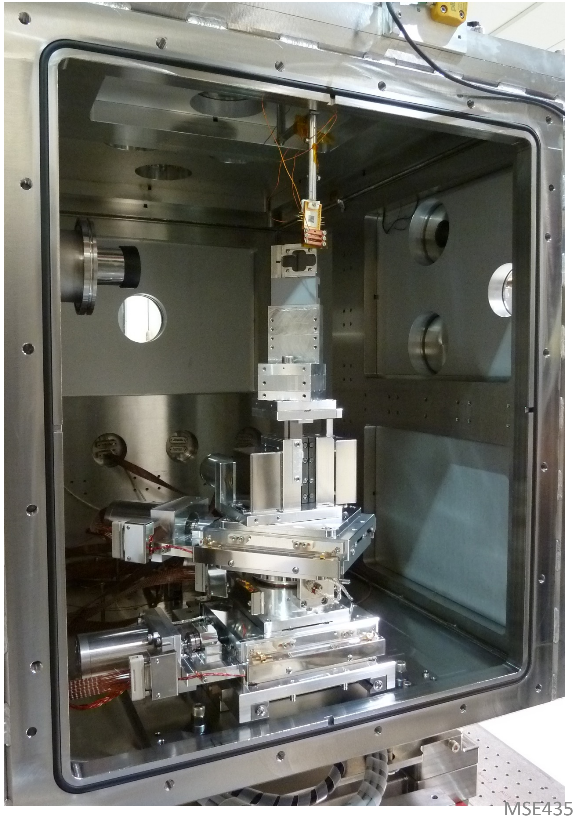
Scanning fluorescence microscopy

Emission spectroscopy (2.25-2.8 keV, planned full range 2.05-4.5 keV)

Using KLM-edges, see all elements from O to U

Topics Material science, new electronic material, environmental sciences, biology, geology, catalysis, flexibility for *in situ* experiments

Vacuum endstation of PHONIX beamline



Challenge:

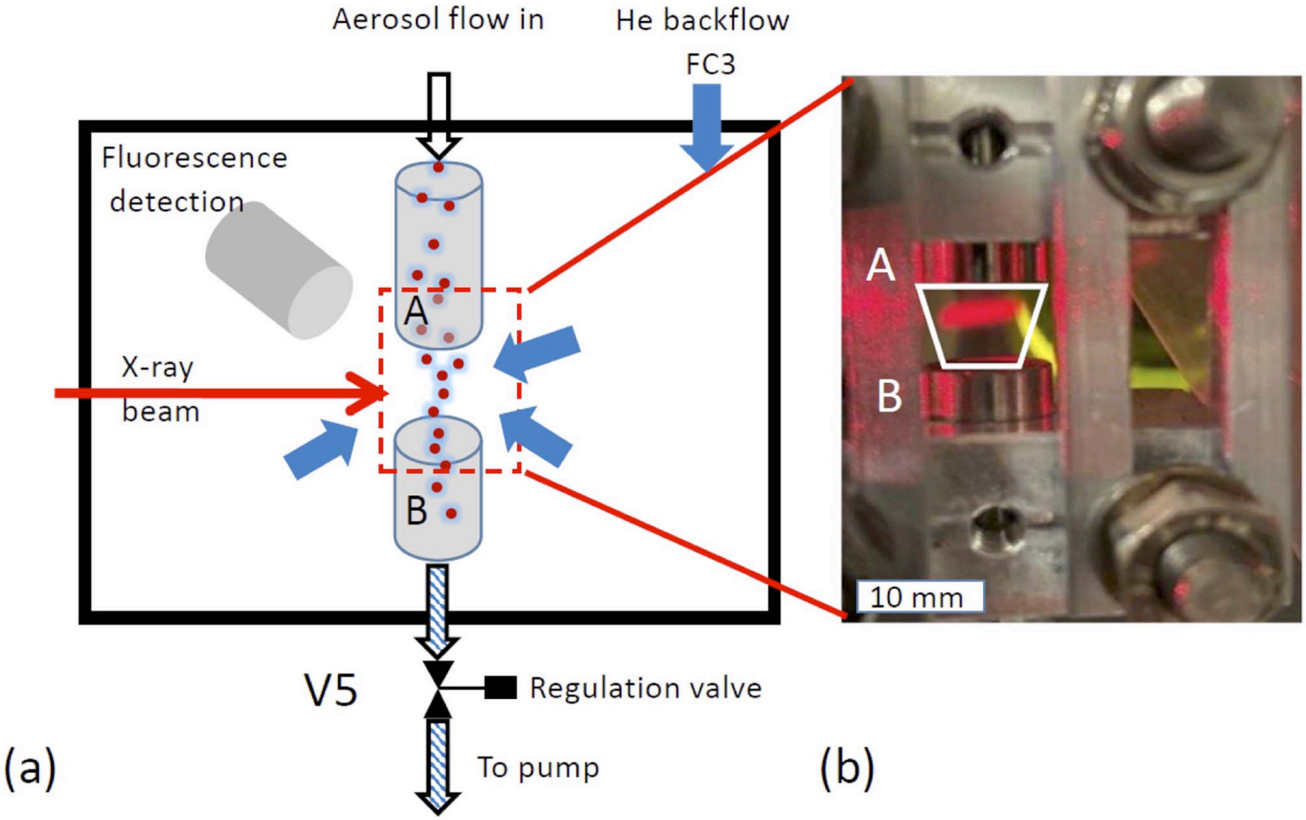
How to study high vapor pressure materials?

How to study gas-solid interactions?

Use cell with window

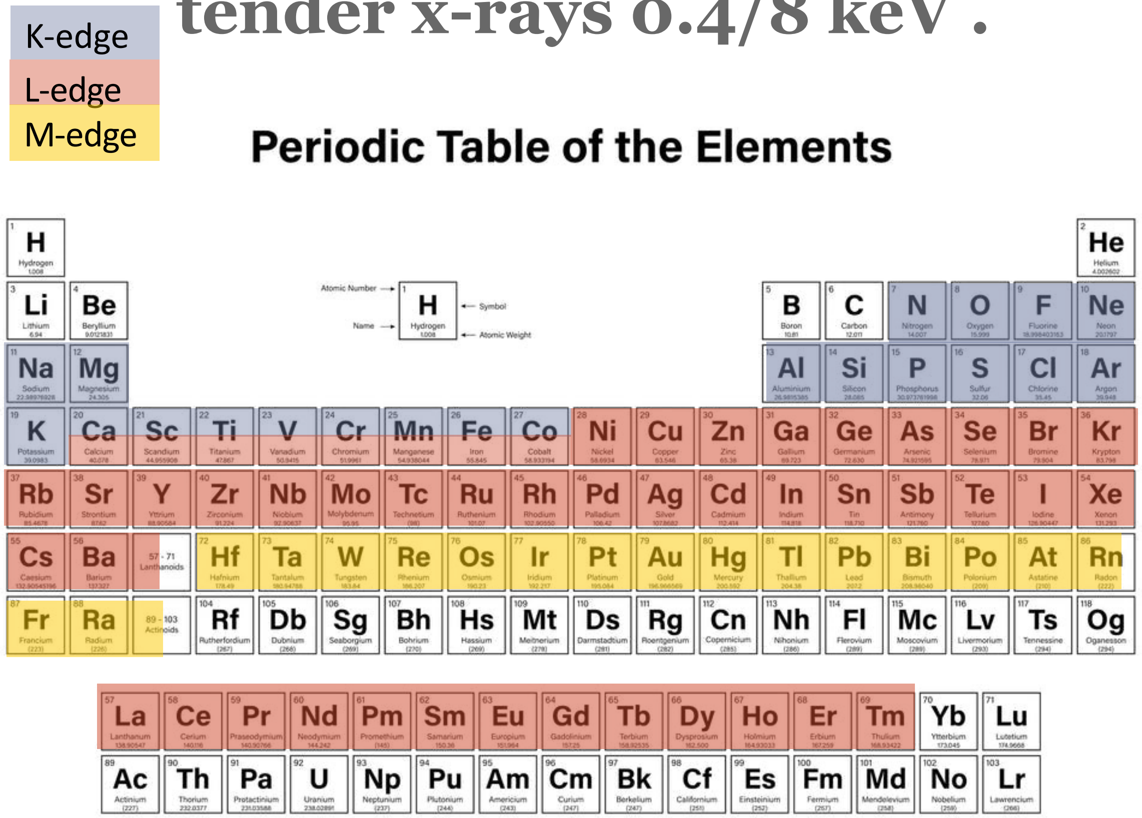
Cell with silicon nitride window
Very stable 1X1 mm 100 nm   1bar

Spectroscopy on airborne particles



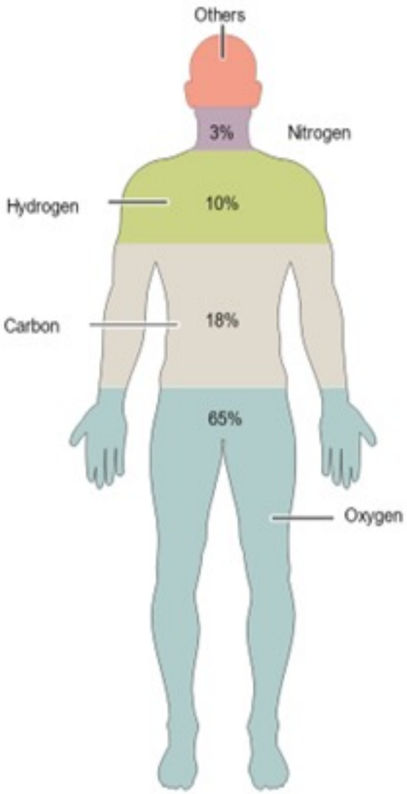
Accessible edges in for soft and tender x-rays 0.4/8 keV .

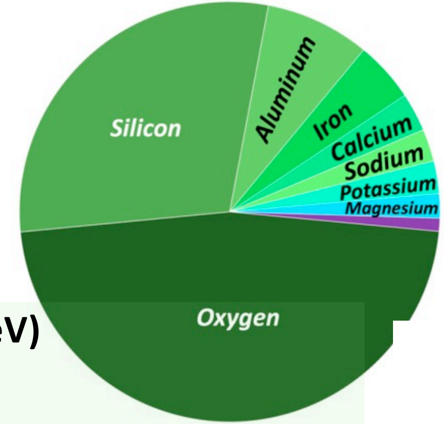
The PHOENIX beamline



Low-Z elements

Most common materials on earth





Relative abundance of Rare Earth Elements

Low Z-elements: C-Fe (0.3-8 keV)

abundant on Earth

Biology: occur in human body **(C,P,S)**

Energy research: Use in Batteries (Li), new: **Na, S, P**

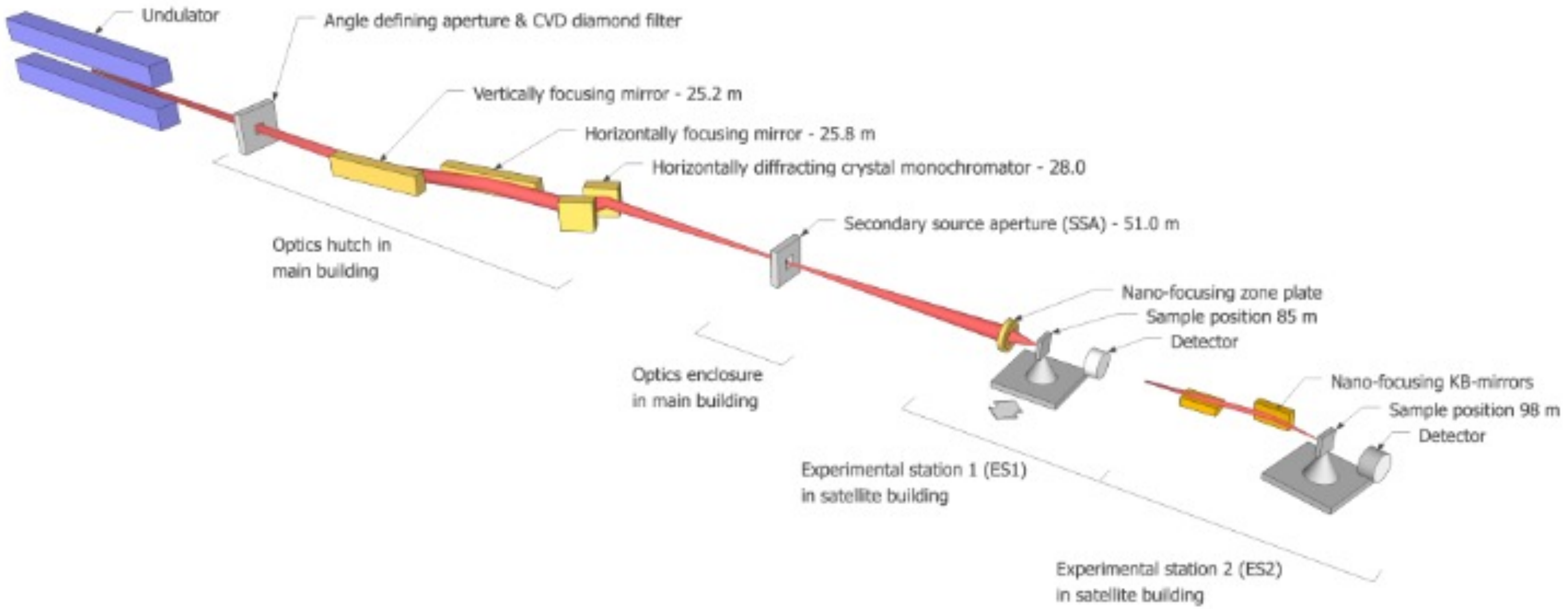
Carbon storage technologies e.g. $CaMgCO_3$

Cement formation **(Al, Si, Mg, Ca**)

Catalysis : Zeolites (**Al, Si**)

Examples of other beamlines

NanoMAX at MAXIV: 98m long for a small focus



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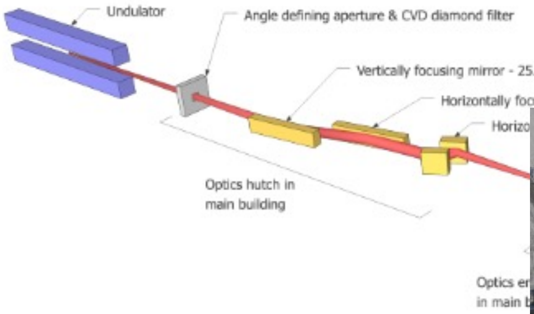
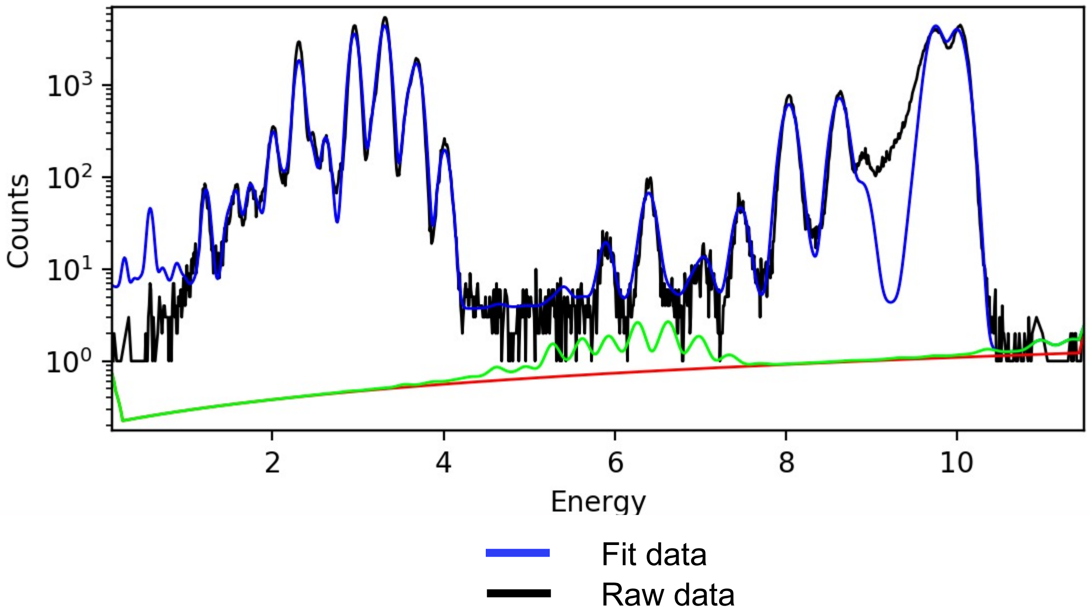
NanoMAX at MAXIV: 98m long for a small focus



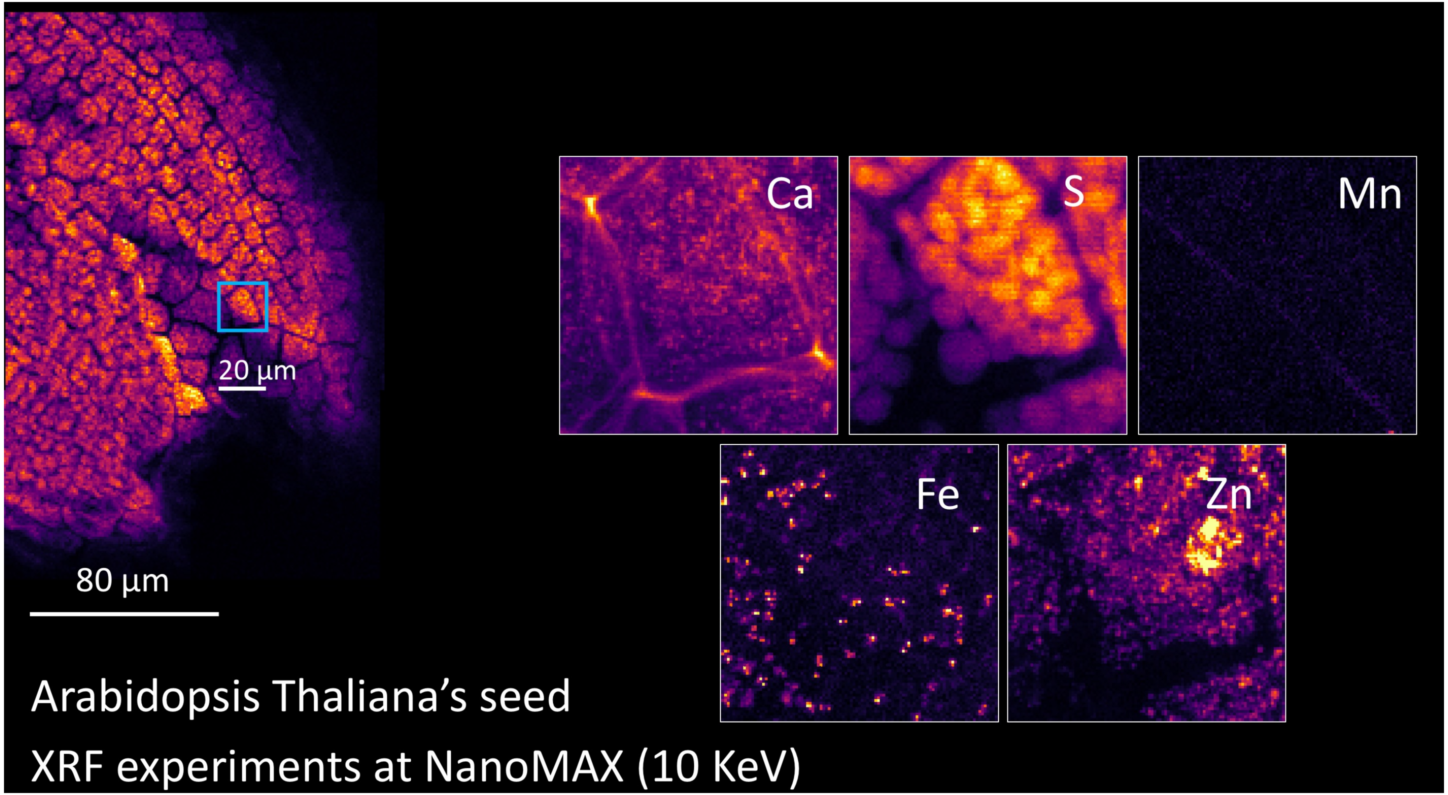
XRF: X-ray fluorescence spectroscopy

XRF experiments at NanoMAX (10 KeV)



Sandra Cuellar-Baena, MAXIV

XRF: X-ray fluorescence spectroscopy



NanoMAX@MAXIV: 60 nm beamsize at 14keV energy

Sandra Cuellar-Baena, MAXIV