



Marianne Liebi– Material Science at Large Scale Facilities

X-ray Fluorescence Spectroscopy (XRF)

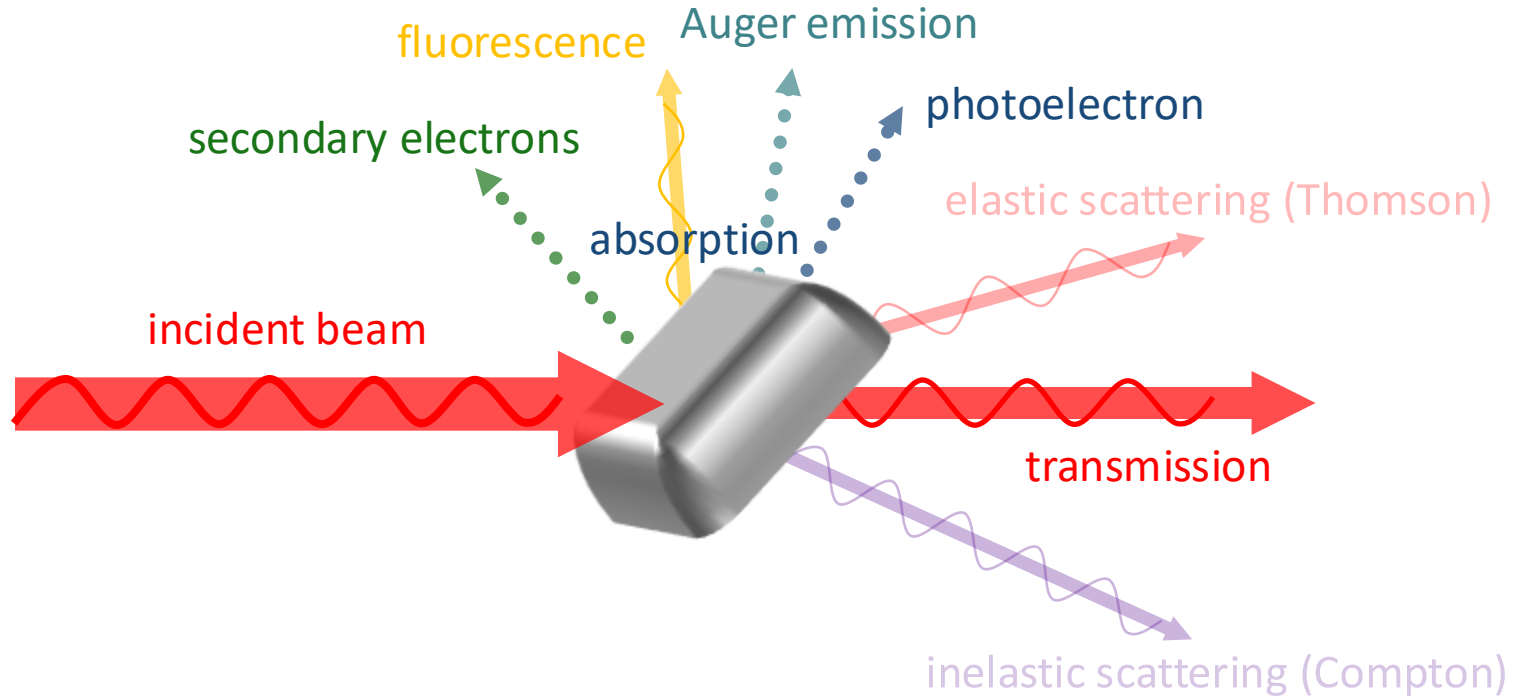
EPFL Master Course 2025 MSE435

Course program

Dates	Content	Lecturer
08.09.25	Introduction, sources, beamlines, detectors	Steven Van Petegem
15.09.25	Excursion to PSI	Marianne Liebi
22.09.25	Holiday	
29.09.25	Interaction with matter	Steven Van Petegem
06.10.25	Fluorescence	Marianne Liebi
13.10.25	X-ray absorption spectroscopy	Marianne Liebi
20.10.25	Break	
27.10.25	Diffraction I	Steven Van Petegem
03.11.25	Small angle scattering	Marianne Liebi
10.11.25	Diffraction II	Steven Van Petegem
17.11.25	Phase contrast / Tomography	Steven Van Petegem
24.11.25	Coherent imaging	Marianne Liebi
01.12.25	Neutron imaging	Steven Van Petegem
08.12.25	PEEM / Magnetic scattering	Steven Van Petegem
15.12.25	Case study presentations	Steven Van Petegem / Marianne Liebi

Virtual tour SLS

Interaction of X-ray with matter

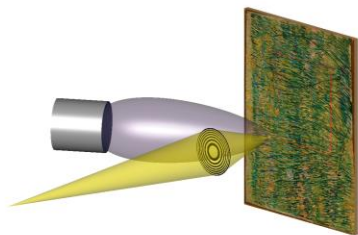


Spectroscopy

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

Microspectroscopies and spectromicroscopies

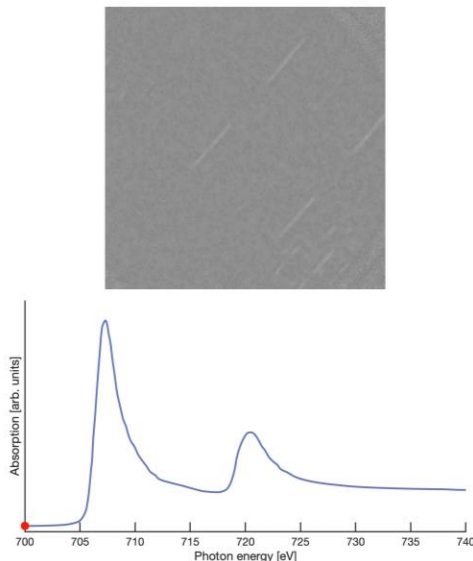
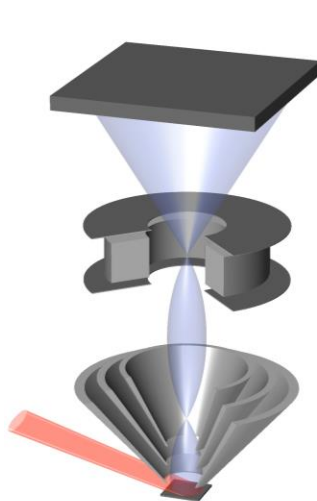
Microspectroscopies: record energy spectra by scanning a focused incident beam over the sample



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 (<i>also consider the direction of incoming and outgoing beam</i>)	ARPES	Electronic structure, surface and interface science
X-ray photoelectron spectroscopy (<i>measurements of directly ejected electrons, information of core or valence state from which the electrons originated</i>)	XPS	Chemistry, surface/absorbate structure, interface chemistry

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.

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Variations
of XAS

not covered in
this course

Overview of spectroscopy techniques

Technique	Abbreviation	Scanned $h\nu_{in}$?
X-ray absorption near-edge spectroscopy	XANES	✓
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	✓
Angle-resolved photoelectron spectroscopy	ARPES	(✓)
X-ray photoelectron spectroscopy	XPS	(✓)

Variations of XAS

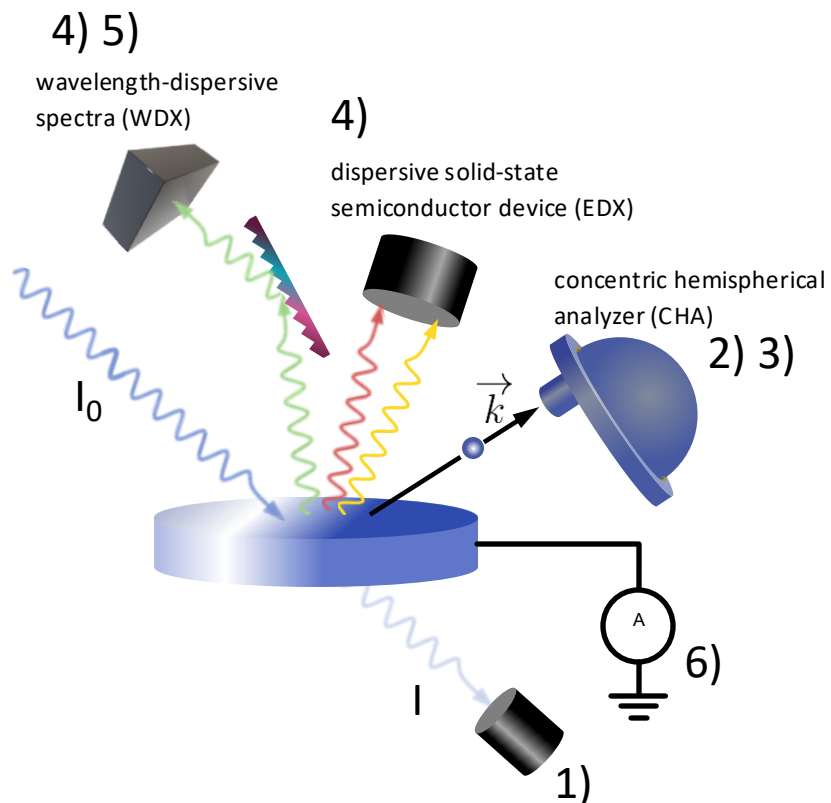
not covered in this course

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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

Overview of spectroscopy techniques

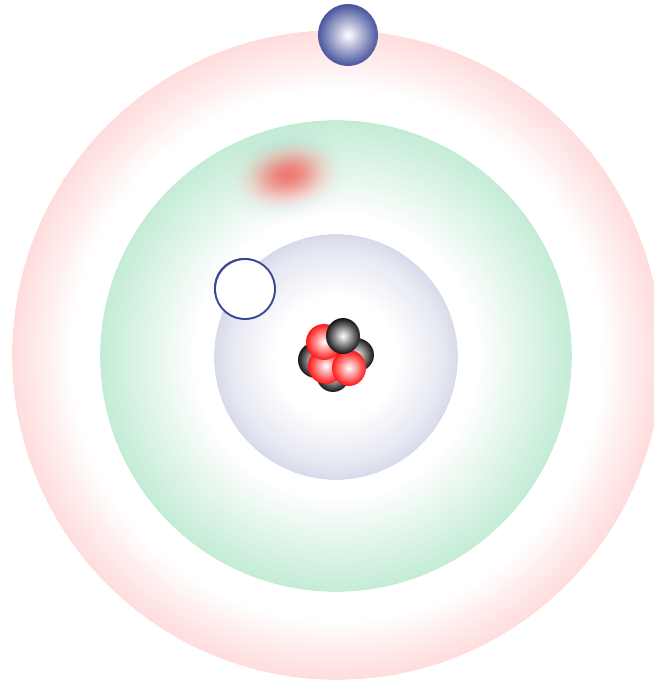
Technique	Abbreviation	Scanned $h\nu_{in}$?	Detection methods
X-ray absorption near-edge spectroscopy	XANES	✓	1, 2, 4, 6
Photoemission electron microscopy	PEEM	✓	6
Scanning transmission x-ray microscopy	STXM	✓	1, 3
Extended x-ray absorption fine structure	EXAFS	✓	1, 2, 4, 6
X-ray fluorescence	XRF		4
Resonant inelastic x-ray scattering	RIXS	✓	5
Angle-resolved photoelectron spectroscopy	ARPES	(✓)	2
X-ray photoelectron spectroscopy	XPS	(✓)	2, 3

Variations of XAS

not covered in this course

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Photoelectrons and fluorescence



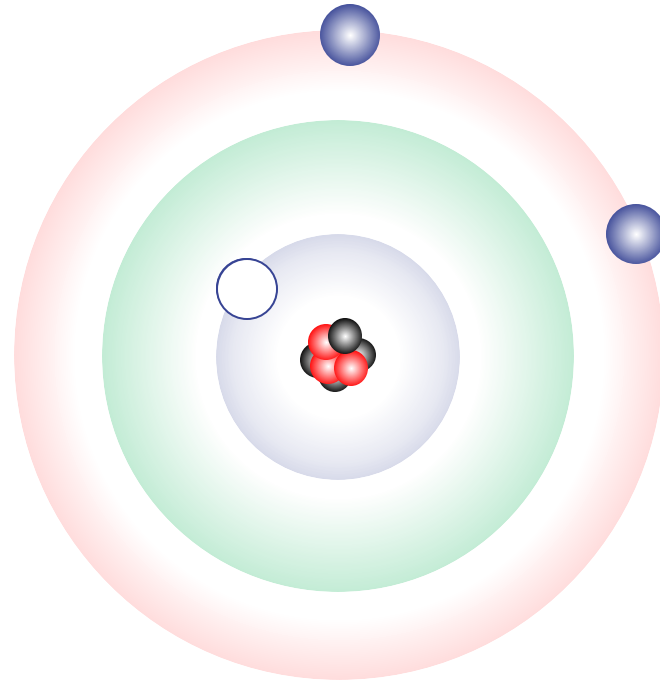
Photoelectron

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

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

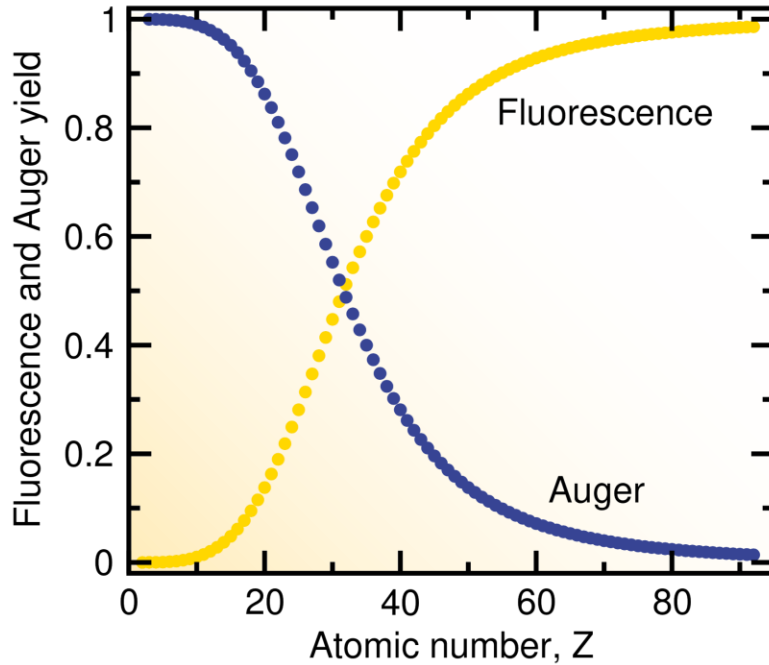
$$h\nu_{out} = E_{B,1} - E_{B,2}$$

Auger electrons



Auger-electron
KE independent of $h\nu$

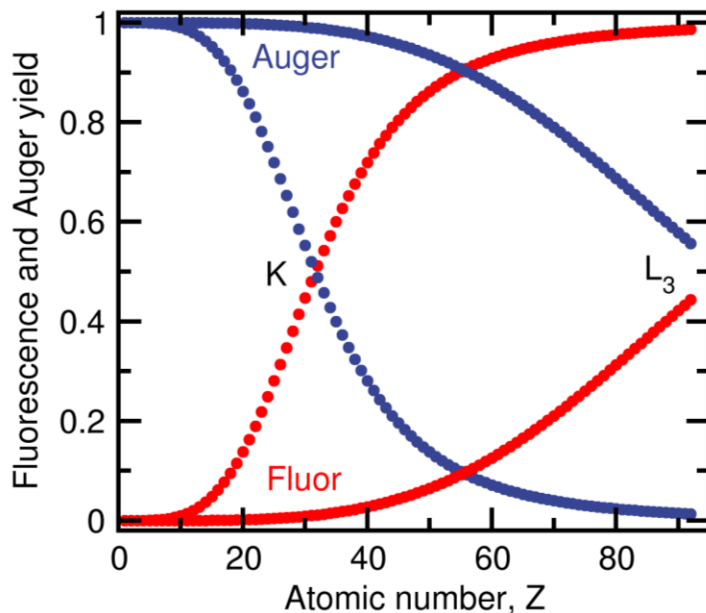
Fluorescence or Auger?



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

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

Fluorescence or Auger?



Fluorescence

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

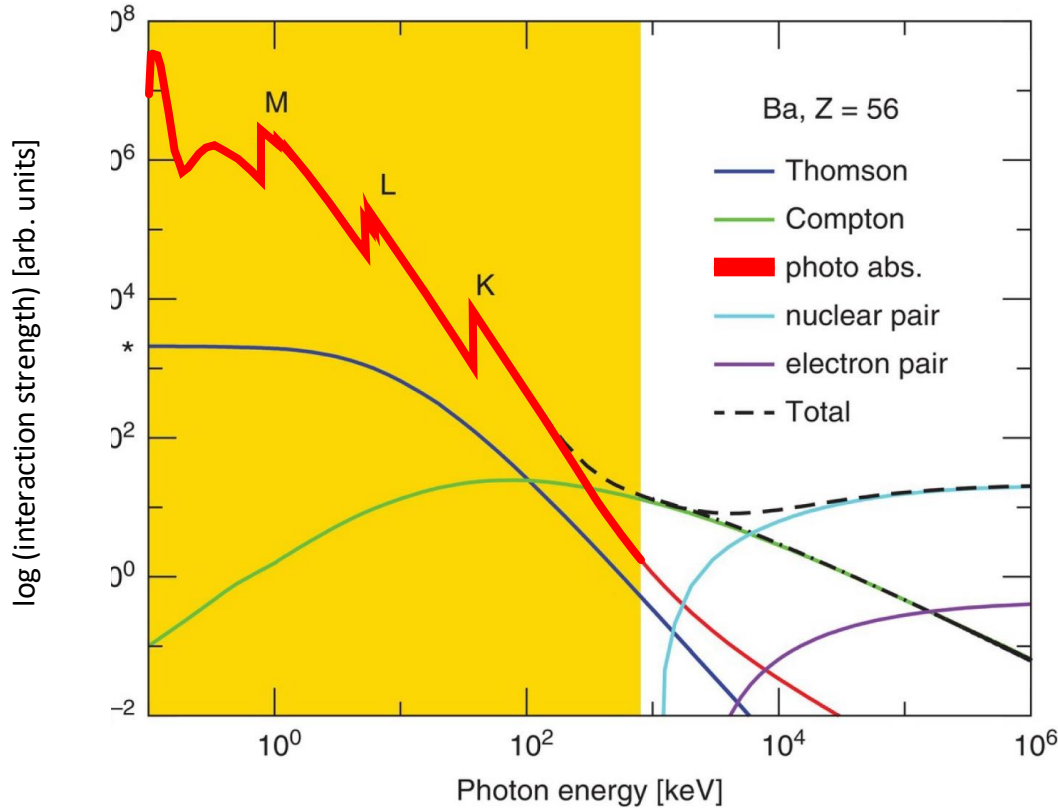
$$A_{21} \propto \hbar \nu^3$$

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

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

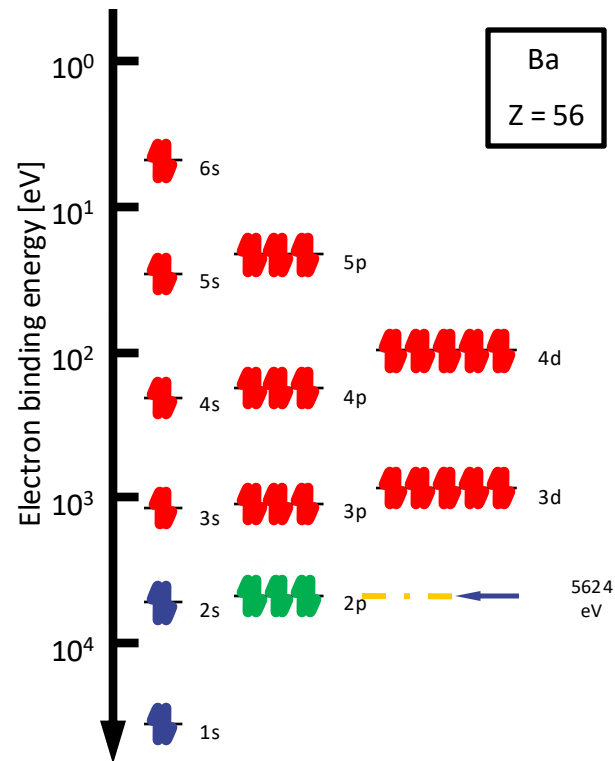
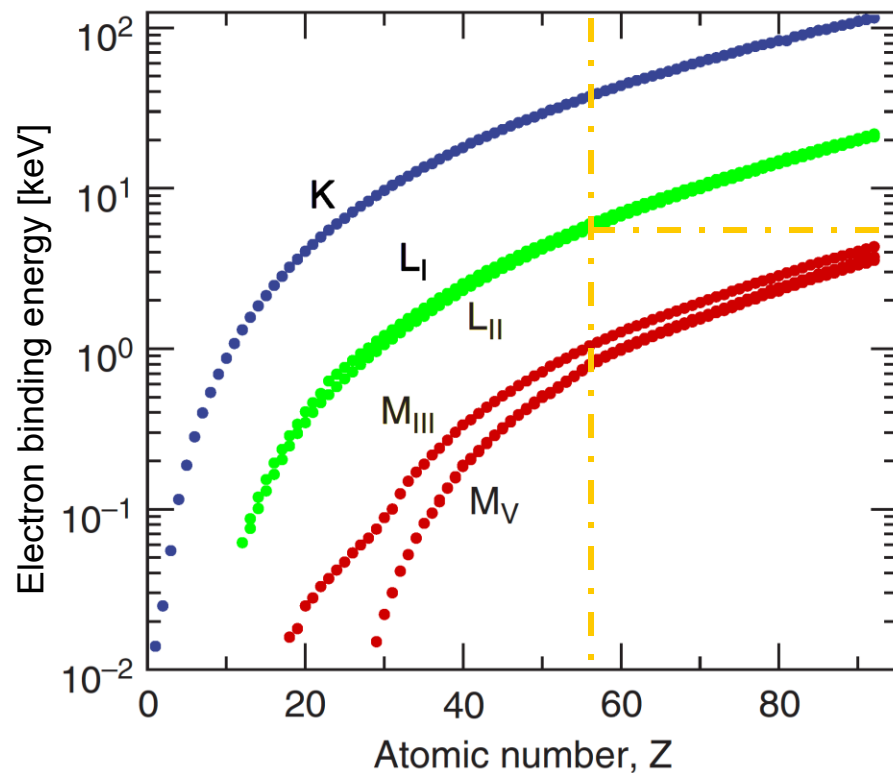
$$A_K \approx 10^6 \quad A_{L_3} \approx 9 \times 10^7$$

Interaction strengths of photo absorption

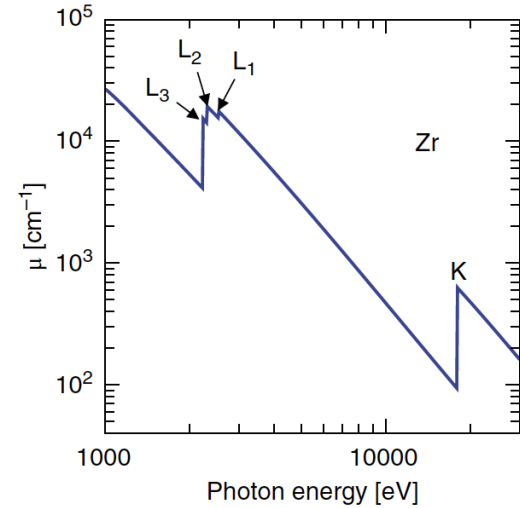
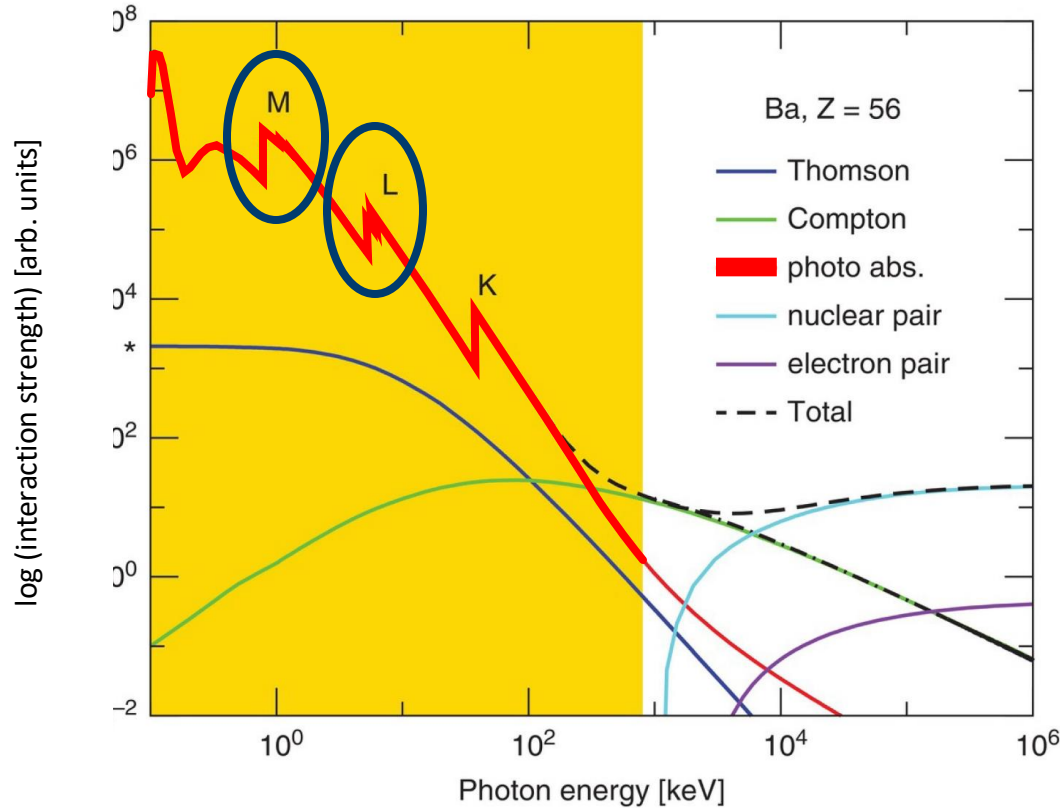


absorption cross-section varies approximately as the third power of the photon energy, interrupted by step-like increases in absorption as the photon energy matches the ionization potential of an occupied electron state in the atom.

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”

X-ray fluorescence emission lines

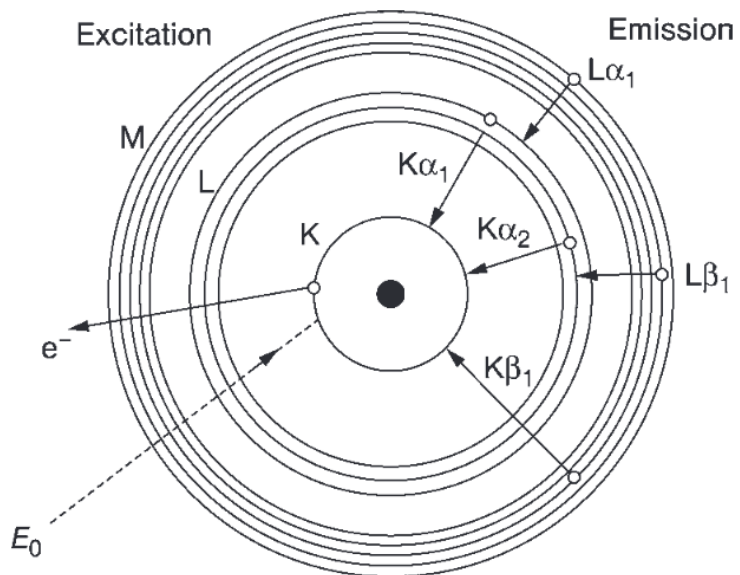


Figure 1. Scheme of X-ray fluorescence: an electron in the K shell is ejected from the atom by an incident photon of energy E_0 (dashed line). The vacancy is filled by an electron from the L shell and K X rays are emitted, in competition with Auger electrons

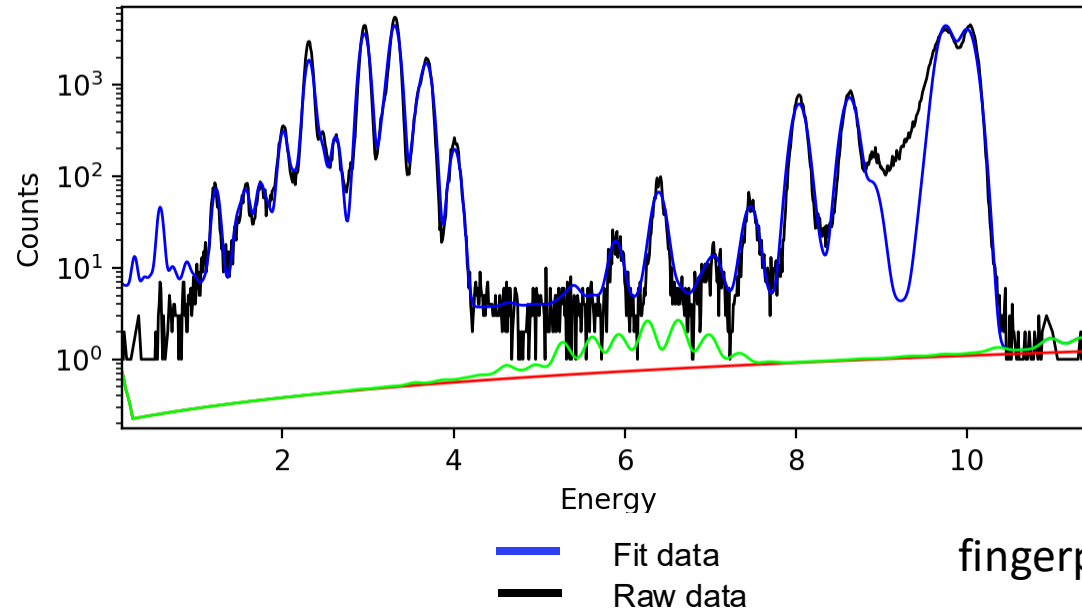
Theoretically, when K shells are excited, four lines are emitted by each element: K_{α_1} , K_{α_2} , K_{β_1} , and K_{β_2} . When L shells are excited, nine lines are emitted by each element, i.e., L_{α_1} , L_{α_2} , L_{β_1} , L_{β_2} , L_{β_3} , L_{γ_1} , L_{γ_3} , L_{λ} , and L_{η} . When M-shells are excited, four lines are emitted, i.e. M_{α_1} , M_{α_2} , M_{β} , and M_{γ} .

From a **practical point** of view, and because of the finite energy the line combinations $L_{\alpha_1}-L_{\alpha_2}$ and $L_{\beta_1}-L_{\beta_2}-L_{\beta_3}$ approximately coincide in a unique larger peak, and the same happens for the pairs $K_{\alpha_1}-K_{\alpha_2}$ and $K_{\beta_1}-K_{\beta_2}$, 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_{γ_1} , L_{γ_3} , L_{λ} , and L_{η}** , of which only the first two are of high intensity.

M_{α_1} , M_{α_2} , 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)

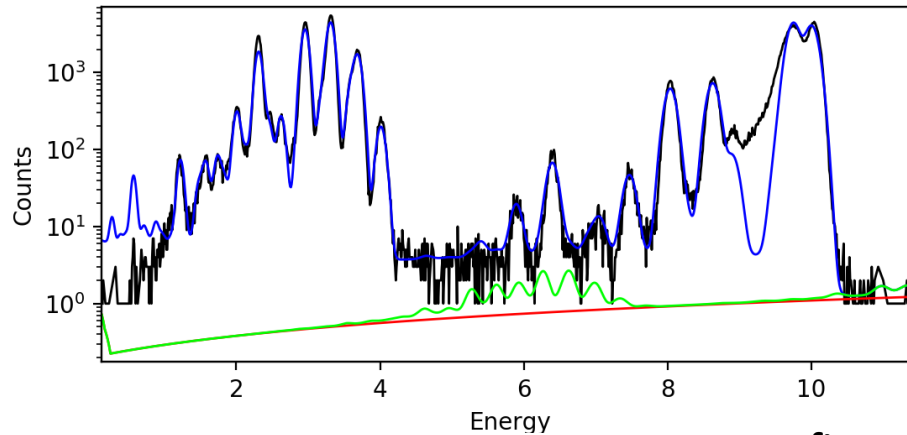
X-ray fluorescence spectrum (measured with 10 keV X-rays)



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/hxrf

1 1.01 H 0.0007 Hydrogen																	2 4.00 He 0.0002 Helium						
3 6.94 Li 0.53 Lithium	4 9.01 Be 1.85 Beryllium K α 0.108																	5 10.81 B 2.34 Boron K α 0.183	6 12.01 C 2.27 Carbon K α 0.277	7 14.01 N 0.001 Nitrogen K α 0.392	8 16.00 O 0.001 Oxygen K α 0.525	9 19.00 F 0.001 Fluorine K α 0.677	10 20.18 Ne 0.0009 Neon K α 0.849
11 22.99 Na 0.97 Sodium K α 1.040	12 24.31 Mg 1.74 Magnesium K α 1.254																	13 26.98 Al 2.70 Aluminium K α 1.486	14 28.09 Si 2.33 Silicon K α 1.740	15 30.97 P 1.82 Phosphorus K α 2.010	16 32.07 S 2.07 Sulfur K α 2.309	17 35.45 Cl 0.003 Chlorine K α 2.622	18 39.95 Ar 0.002 Argon K α 2.958
19 39.10 K 0.86 Potassium K α 3.314	20 40.08 Ca 1.54 Calcium K α 3.692 L α 0.341	21 44.96 Sc 2.99 Scandium K α 4.093 L α 0.395	22 47.87 Ti 4.54 Titanium K α 4.512 L α 0.452	23 50.94 V 6.11 Vanadium K α 4.953 L α 0.510	24 52.00 Cr 7.15 Chromium K α 5.415 L α 0.572	25 54.94 Mn 7.44 Manganese K α 5.900 L α 0.637	26 55.85 Fe 7.87 Iron K α 6.405 L α 0.705	27 58.93 Co 8.86 Cobalt K α 6.931 L α 0.775	28 58.69 Ni 8.91 Nickel K α 7.480 L α 0.849	29 63.55 Cu 8.93 Copper K α 8.046 L α 0.928	30 65.38 Zn 7.13 Zinc K α 8.637 L α 1.012	31 69.72 Ga 5.91 Gallium K α 9.251 L α 1.098	32 72.64 Ge 5.32 Germanium K α 9.886 L α 1.188	33 74.92 As 5.78 Arsenic K α 10.543 L α 1.282	34 78.96 Se 4.81 Selenium K α 11.224 L α 1.379	35 79.90 Br 3.12 Bromine K α 11.924 L α 1.481	36 83.80 Kr 0.004 Krypton K α 12.648 L α 1.585						
37 85.47 Rb 1.53 Rubidium K α 13.396 L α 1.692	38 87.62 Sr 2.64 Strontium K α 14.165 L α 1.806	39 88.91 Y 4.47 Yttrium K α 14.958 L α 1.924	40 91.22 Zr 6.51 Zirconium K α 15.775 L α 2.044	41 92.91 Nb 8.57 Niobium K α 16.615 L α 2.169	42 95.94 Mo 10.23 Molybdenum K α 17.480 L α 2.292	43 98 Tc 11.50 Technetium K α 18.367 L α 2.423	44 101.07 Ru 12.37 Ruthenium K α 19.279 L α 2.558	45 102.91 Rh 12.41 Rhodium K α 20.216 L α 2.697	46 106.42 Pd 12.02 Palladium K α 21.177 L α 2.838	47 107.87 Ag 10.50 Silver K α 22.163 L α 2.983	48 112.41 Cd 8.69 Cadmium K α 23.173 L α 3.133	49 114.82 In 7.31 Indium K α 24.210 L α 3.286	50 118.71 Sn 7.29 Tin K α 25.271 L α 3.444	51 121.76 Sb 6.69 Antimony K α 26.359 L α 3.604	52 127.60 Te 6.23 Tellurium K α 27.473 L α 3.768	53 126.90 I 4.93 Iodine K α 28.612 L α 3.938	54 131.29 Xe 0.006 Xenon K α 29.775 L α 4.110						
55 132.91 Cs 1.87 Cesium K α 30.973 L α 4.285	56 137.33 Ba 3.59 Barium K α 32.194 L α 4.466	57 138.91 La 6.15 Lanthanum K α 33.442 L α 4.647	72 178.49 Hf 13.31 Hafnium K α 7.899 M α 1.646	73 180.95 Ta 16.65 Tantalum K α 8.146 M α 1.712	74 183.84 W 19.25 Tungsten K α 8.398 M α 1.775	75 186.21 Re 21.02 Rhenium K α 8.652 M α 1.843	76 190.23 Os 22.61 Osmium K α 8.911 M α 1.907	77 192.22 Ir 22.65 Iridium K α 9.175 M α 1.980	78 195.08 Pt 21.46 Platinum K α 9.442 M α 2.050	79 196.97 Au 19.28 Gold K α 9.713 M α 2.123	80 200.59 Hg 13.53 Mercury K α 9.989 M α 2.195	81 204.37 Tl 11.85 Thallium K α 10.269 M α 2.271	82 207.20 Pb 11.34 Lead K α 10.551 M α 2.342	83 208.98 Bi 9.81 Bismuth K α 10.839 M α 2.423	84 (209) Po 9.32 Polonium K α 11.131 M α 2.499	85 (210) At 7.00 Astatine K α 11.427 M α 2.577	86 (222) Rn 0.01 Radon K α 11.727 M α 2.654						
87 (223) Fr 1.87 Francium K α 12.031 M α 2.732	88 (226) Ra 5.50 Radium K α 12.339 M α 2.806	89 (227) Ac 10.07 Actinium K α 12.652 M α 2.900																					

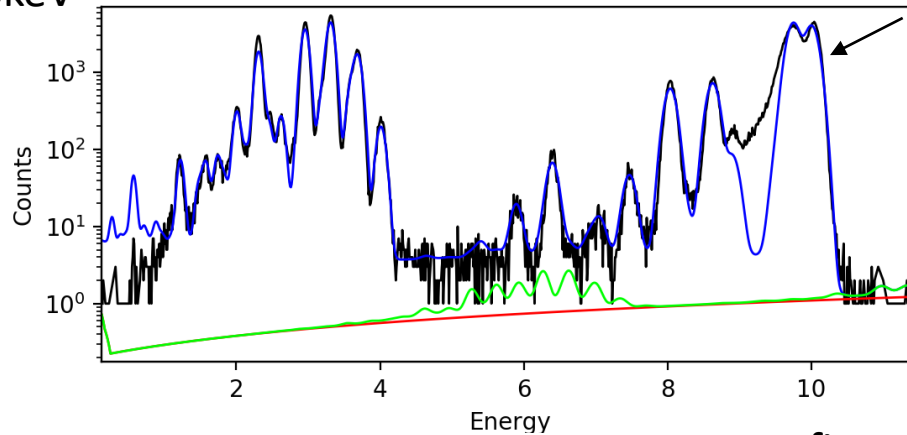
Atomic number		Atomic weight		Density (g/cm ³)		Symbol		Element name		Energy (keV)		Spectral line	
35	79.90	3.12	3.12	Br	Bromine	K α 11.924	L α 1.481						

58 140.12 Ce 6.77 Cerium K α 4.839 M α 0.884	59 140.91 Pr 6.77 Praseodymium K α 5.035 M α 0.927	60 144.24 Nd 7.01 Neodymium K α 5.228 M α 0.979	61 (145) Pm 7.26 Promethium K α 5.432 M α 1.023	62 150.36 Sm 7.52 Samarium K α 5.633 L α 1.078 M α 1.131	63 151.96 Eu 5.24 Europium K α 5.849 L α 6.053 M α 1.181	64 157.25 Gd 7.90 Gadolinium K α 6.273 L α 6.273 M α 1.240	65 158.93 Tb 8.23 Terbium K α 6.498 L α 6.498 M α 1.293	66 162.50 Dy 8.55 Dysprosium K α 6.720 L α 6.720 M α 1.348	67 164.93 Ho 8.80 Holmium K α 6.949 L α 6.949 M α 1.404	68 167.26 Er 9.07 Erbium K α 7.180 L α 7.180 M α 1.462	69 168.93 Tm 9.32 Thulium K α 7.416 L α 7.416 M α 1.526	70 173.04 Yb 6.97 Ytterbium K α 7.616 L α 7.616 M α 1.580	71 174.47 Lu 9.84 Lutetium K α 7.655 L α 7.655 M α 1.580
90 232.04 Th 11.72 Thorium K α 12.968 M α 2.996	91 231.04 Pa 15.37 Protactinium K α 13.291 M α 3.082	92 238.03 U 18.95 Uranium K α 13.614 M α 3.171	93 (237) Np 20.45 Neptunium K α 13.946 M α 3.250	94 (244) Pu 19.84 Plutonium K α 14.282 M α 3.339	95 (243) Am 13.69 Americium K α 14.620 M α 3.438	96 (247) Cm 13.51 Curium K α 14.960 M α 3.537	97 (247) Bk 14.79 Berkelium K α 15.300 M α 3.636	98 (251) Cf 15.1 Californium K α 15.640 M α 3.735	99 (252) Es 13.5 Einsteinium K α 15.980 M α 3.834	100 (257) Fm 13.5 Fermium K α 16.320 M α 3.933	101 (258) Md 13.5 Mendelevium K α 16.660 M α 4.032	102 (259) No 13.5 Nobelium K α 17.000 M α 4.131	103 (262) Lr 13.5 Lawrencium K α 17.340 M α 4.230

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



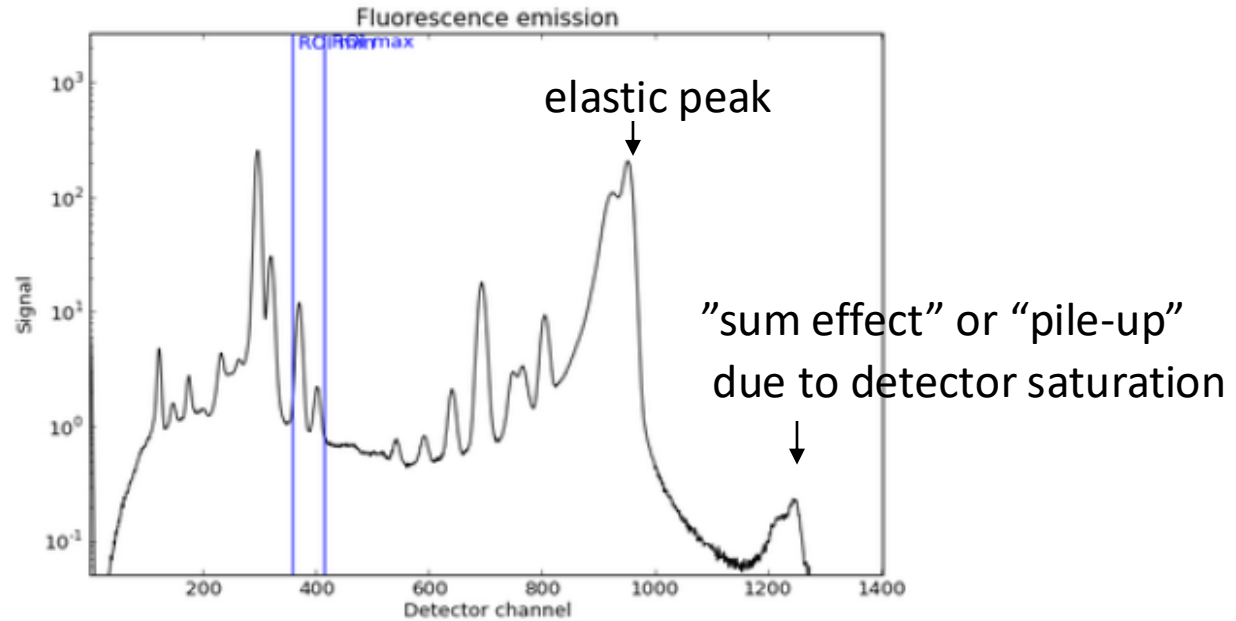
elastic scattering

fingerprint of elements

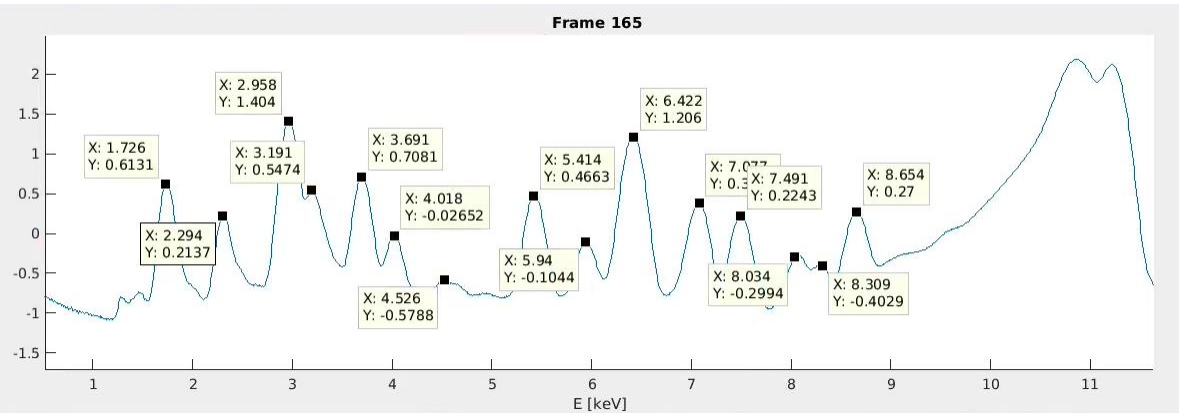
X-ray fluorescence spectrum

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- 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 processed 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)



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

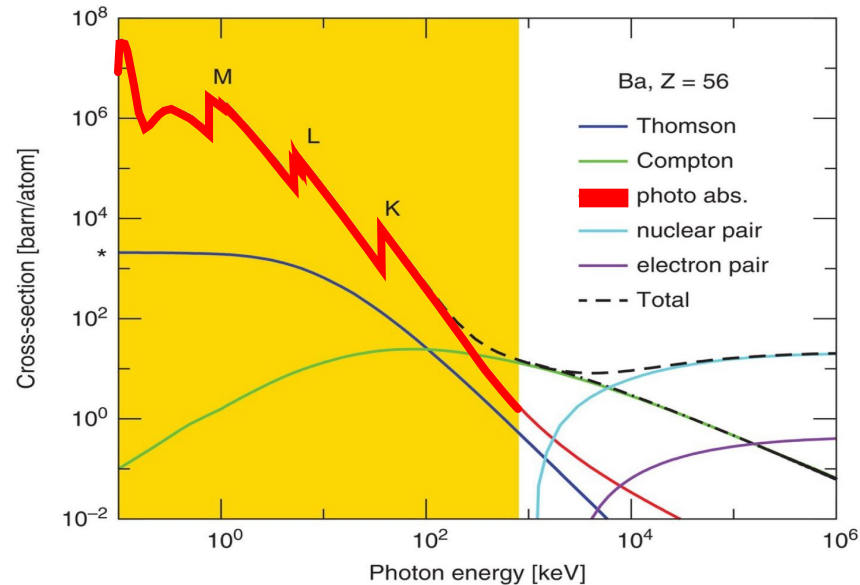
7.49 Ni

8.03 & 8.3 Cu

8.65 Zn

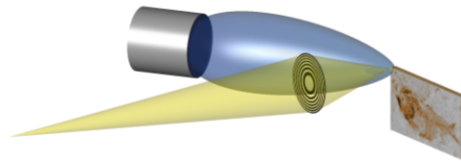
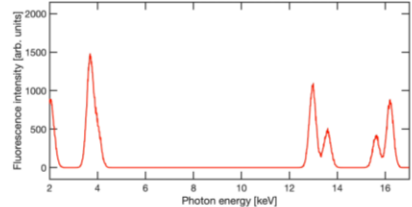
XRF at Labsource vs. Synchrotron

- 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



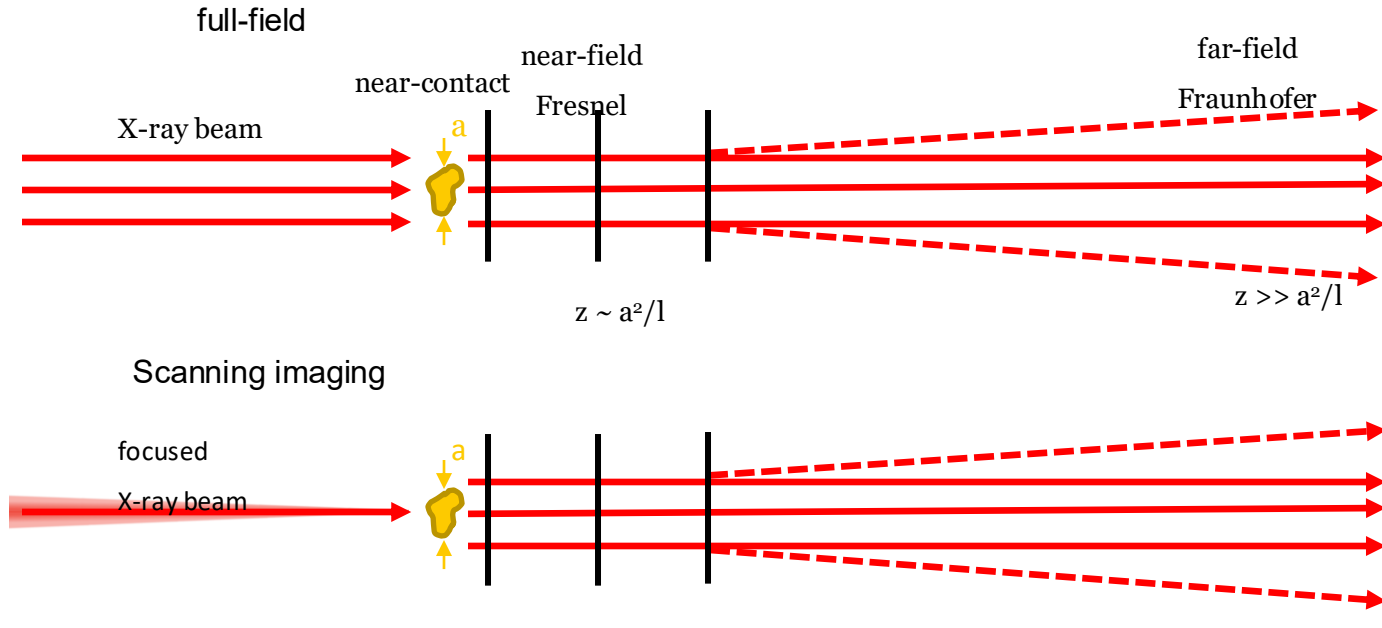
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- X-ray energy has to be higher than the excitation energy of the probed element
- for a specific element to increase sensitivity: largest cross-section just above the edge
- high flux and small beam \rightarrow high spatial resolution and high sensitivity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

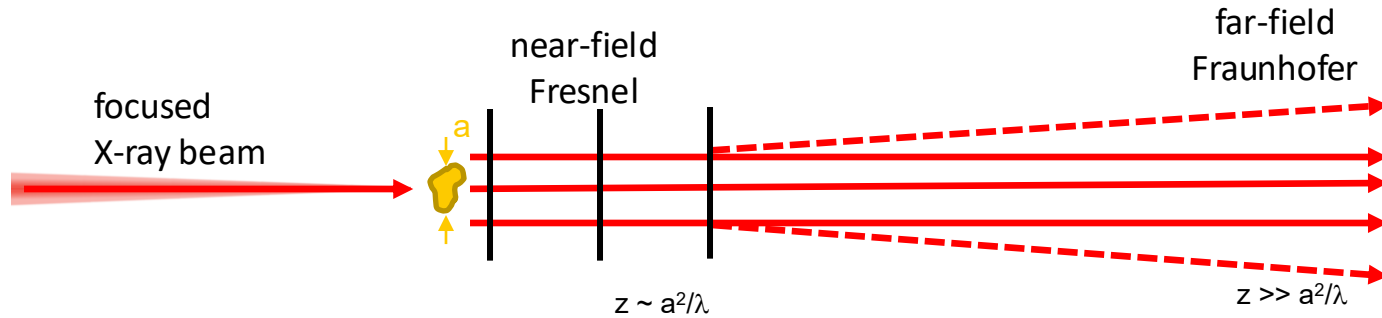


scanning XRF: Microspectroscopy

X-ray imaging



X-ray imaging: scanning

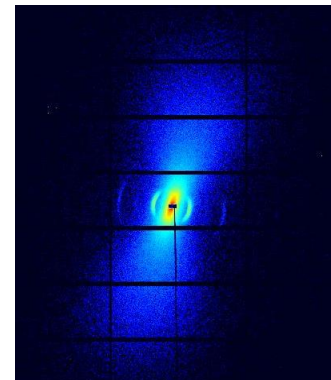
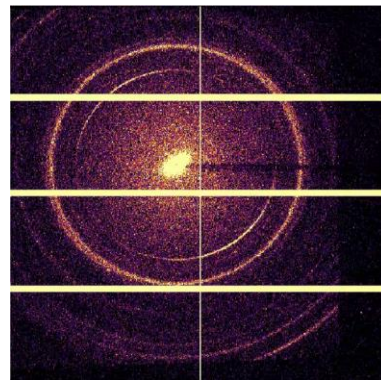
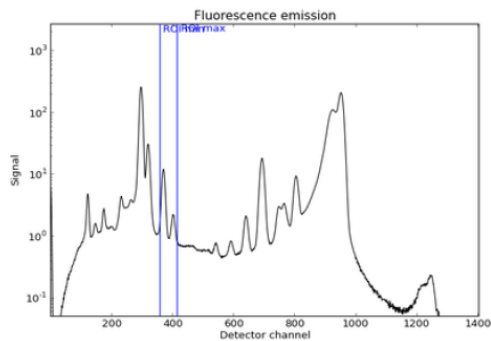
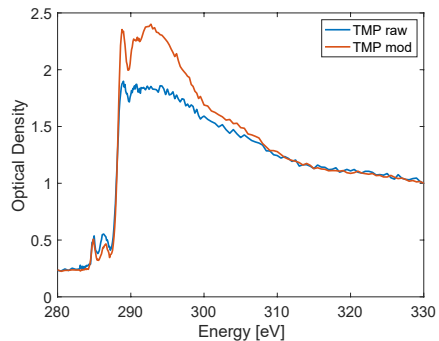
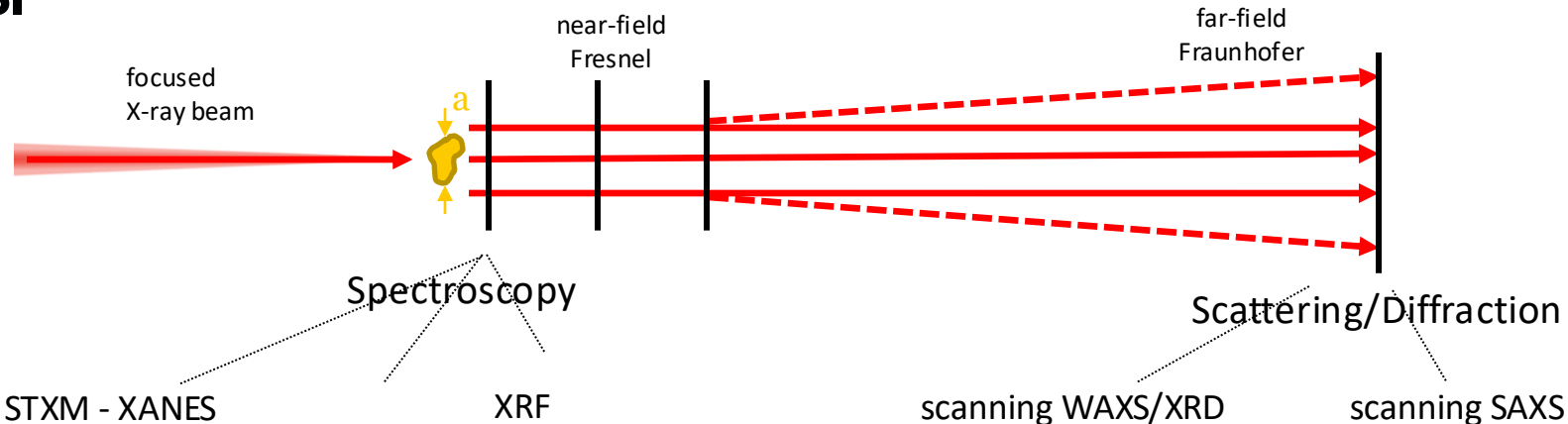


scanning transmission X-ray microscopy STXM

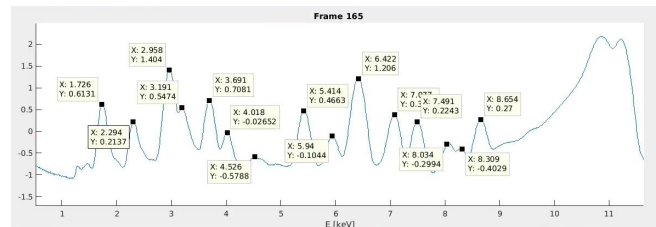
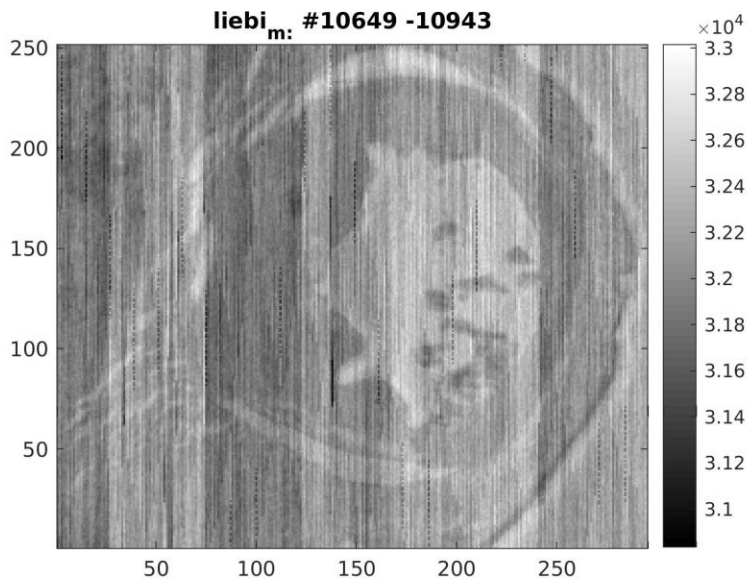
raster scanning of the sample: slow technique

not only absorption/phase can be probed, but in each point one can probe the interaction of X-ray with matter with eg. 2D detectors for scattering/diffraction, fluorescence detectors for spectroscopy

X-ray scanning imaging

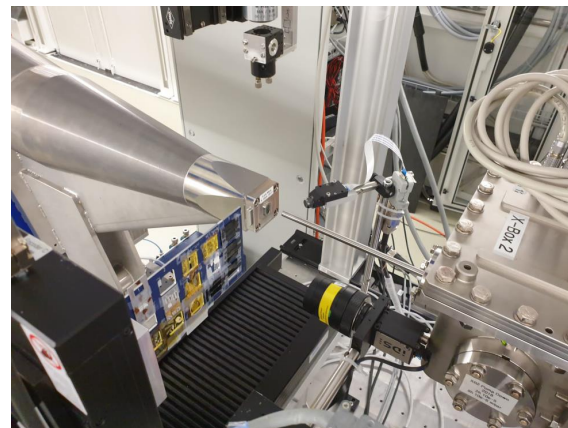


XRF measurement at cSAXS



thin section of umbilical cord with calcifications
measured at cSAXS
12um x 8 um beamsize
11.2 keV

transmission signal (and top-up of SLS!)



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:

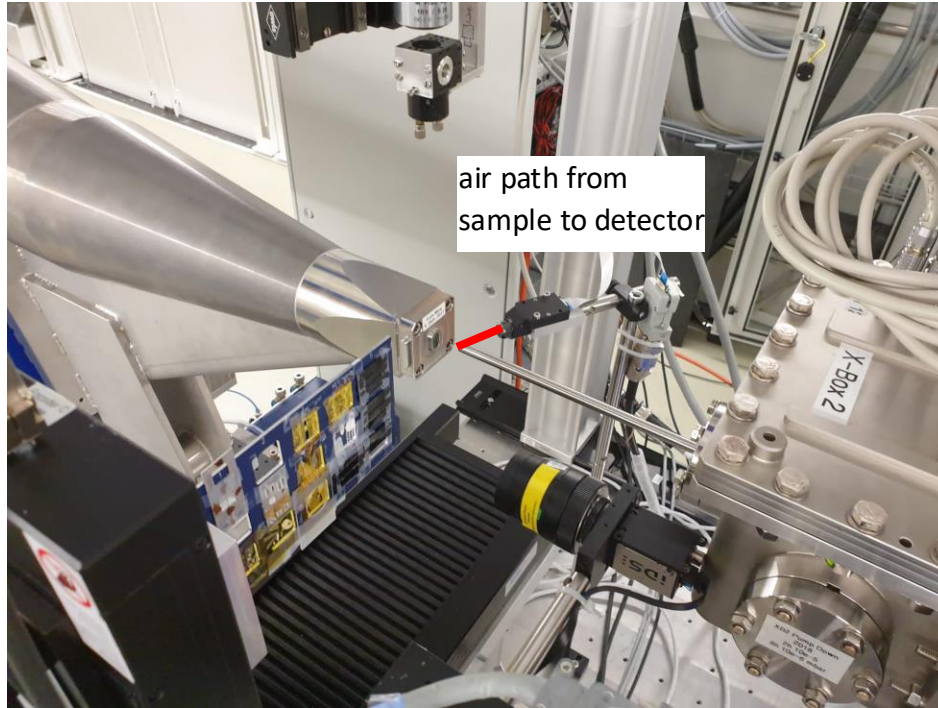
<https://www.maxiv.lu.se/beamlines-accelerators/beamlines/nanomax/user-information/experimental-station/data-access-and-processing/>

- 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

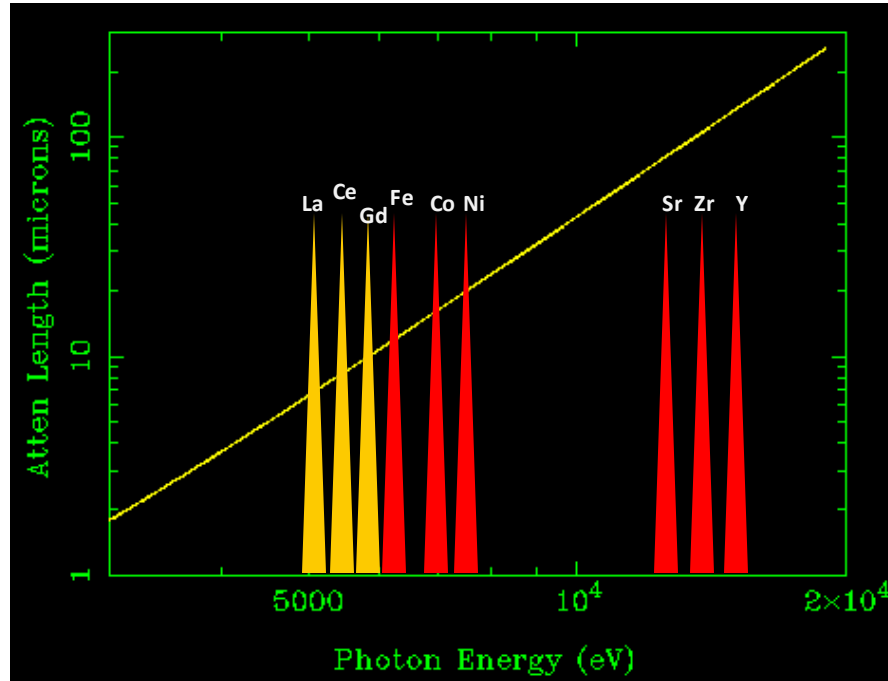
- To analyze samples quantitatively an X-ray fluorescence reference standard is normally used. A typical standard is a thin film sample, where several elements have been deposited on a very thin silicon nitride window.
- for example AXO Dresden: http://www.axo-dresden.de/mainframe_reference.htm
- The 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 heterogeneous samples

Absorbance in air and self-absorbance



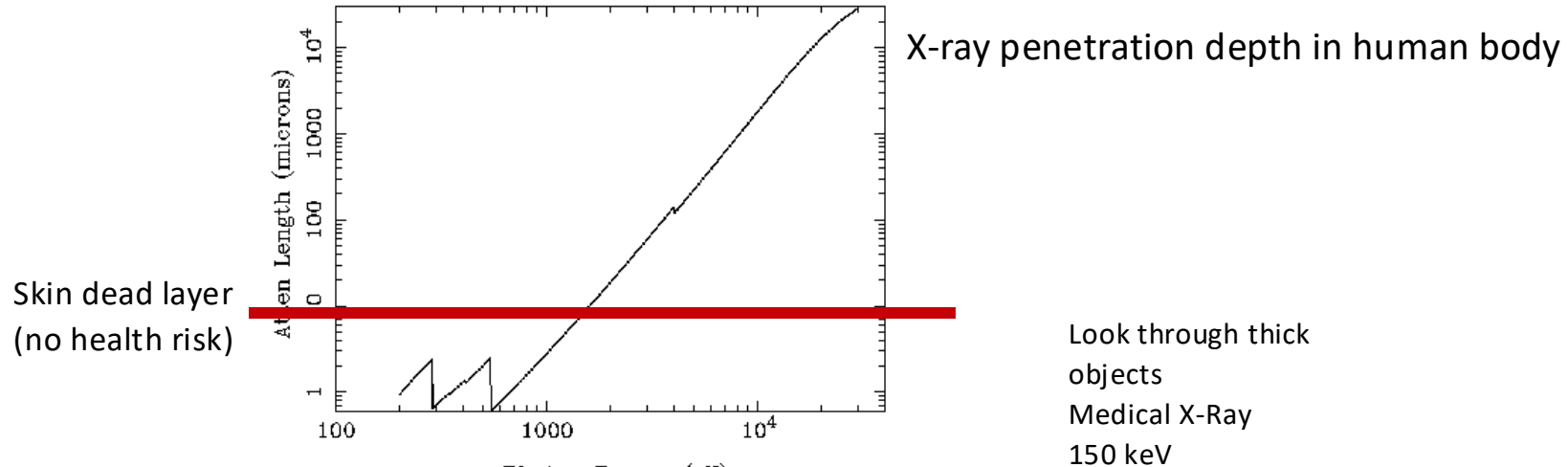
- air path: absorbance of lower-energy lines \rightarrow measurement in vacuum is beneficial
- self-absorbance within the sample: quantification of thicker samples is very complicated (in particular for heterogeneous samples)
- for lower energies only the last layer probed \rightarrow different resolution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

What elements we want to see? What sample size?

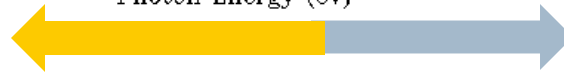


Solid Oxide Fuel/Electrolyzer Cell

X-ray Penetration depth in human body



Work in He / Vacuum



Work in air

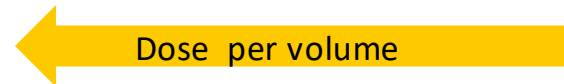
Thin sample

**sensitivity to smaller
total amounts**



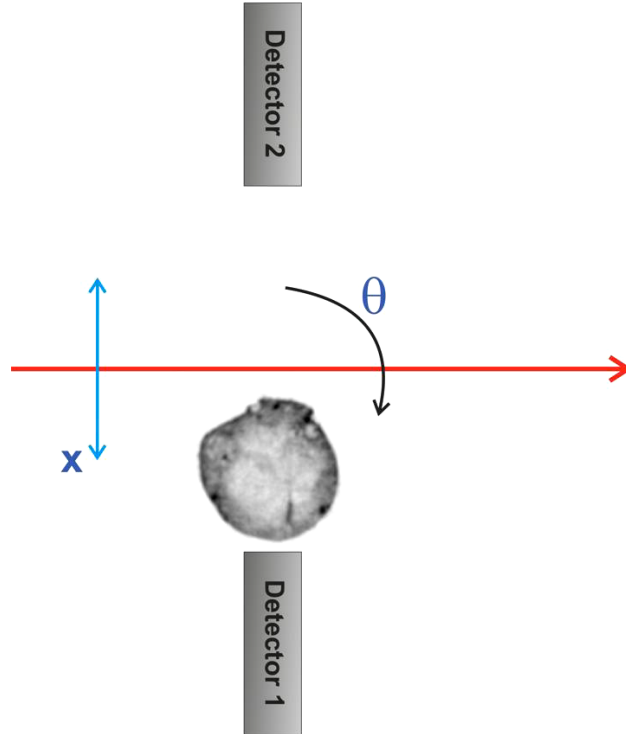
Thick sample

More Radiation damage

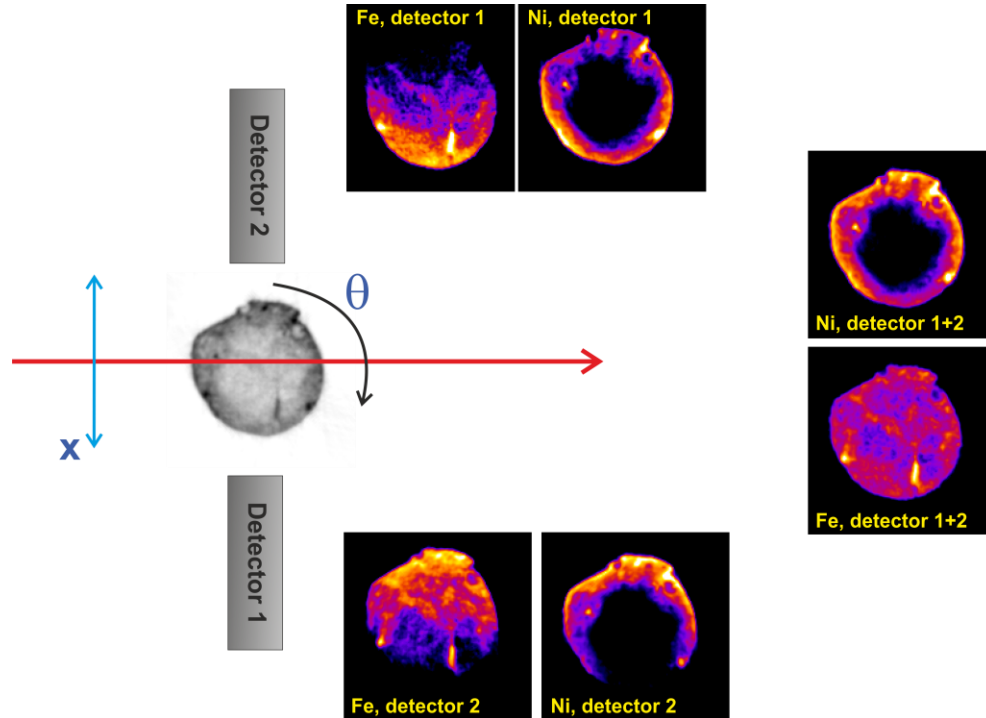


Dose per volume

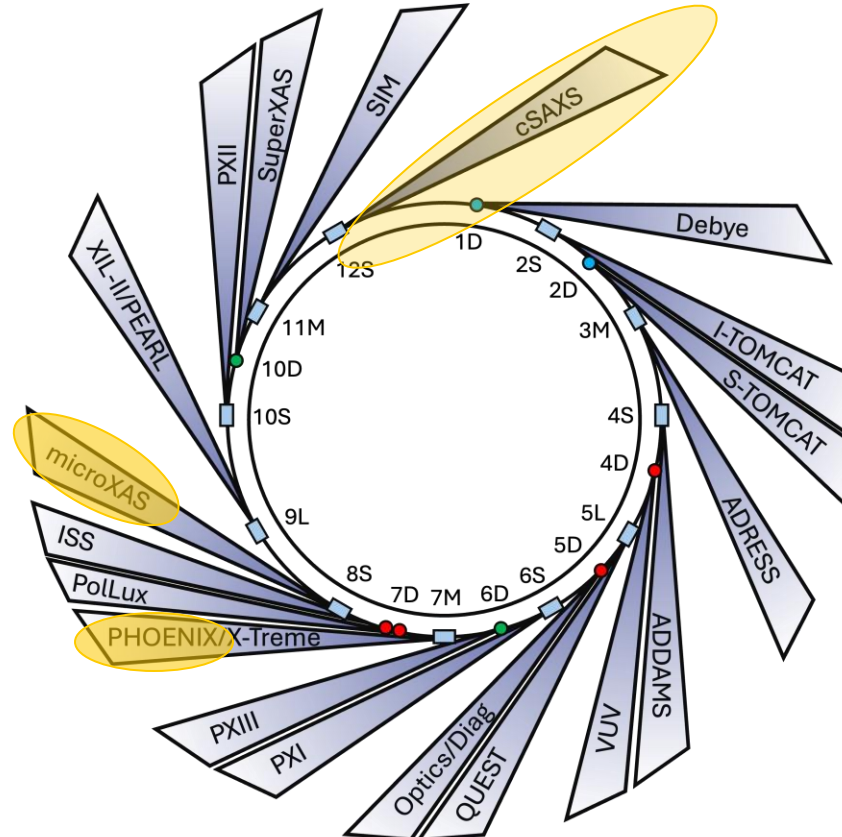
μ XRF scanning tomography



μ XRF scanning tomography: self-attenuation

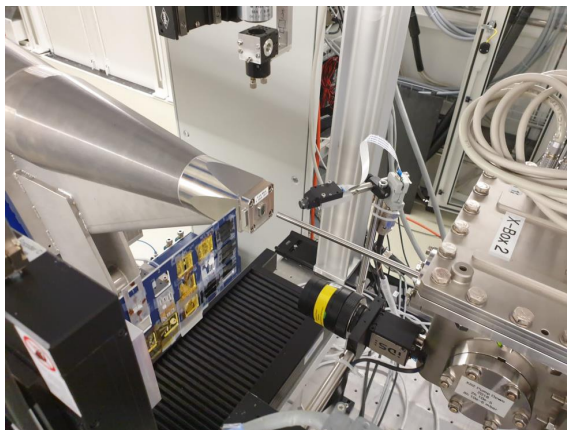


XRF @ PSI



SLS beamlines with XRF capabilities

cSAXS



microXAS



PHOENIX beamline

XAS in tender energy range

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

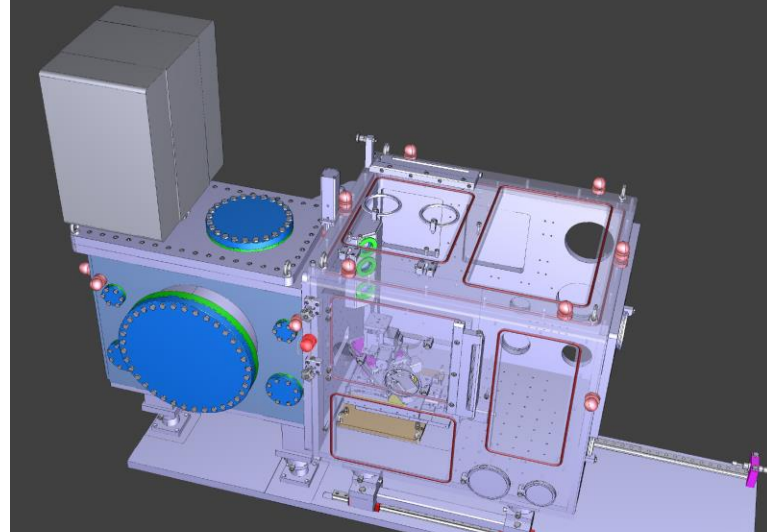
PHOENIX II 0.4-2 keV planar grating, microfocus 4X5 mm

Scanning fluorescence microscopy

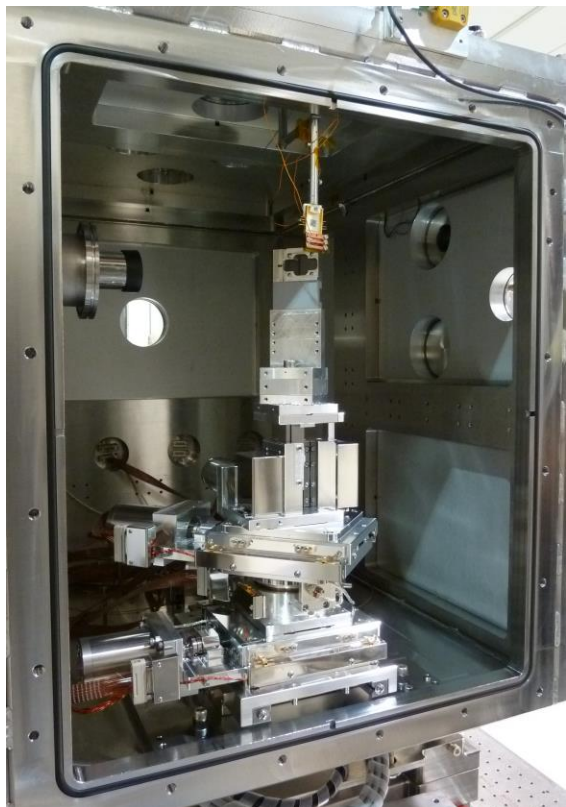
Emission spectroscopy (2.25-2.8 keV, planned full range 2.05-4.5 keV)

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:

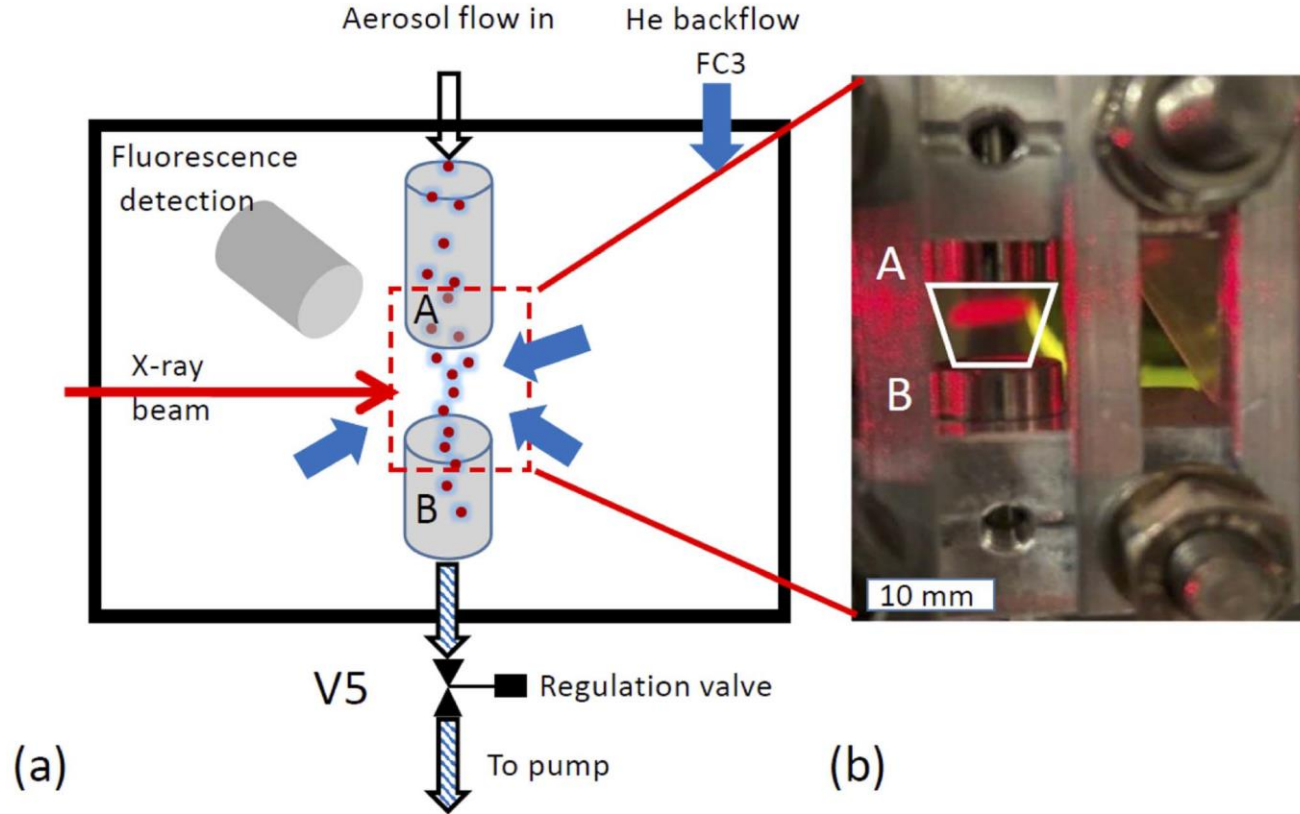
How to study high vapor pressure materials?

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

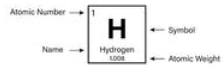


Accessible edges in for soft and tender x-rays 0.4/8 keV .

- K-edge
- L-edge
- M-edge

Periodic Table of the Elements

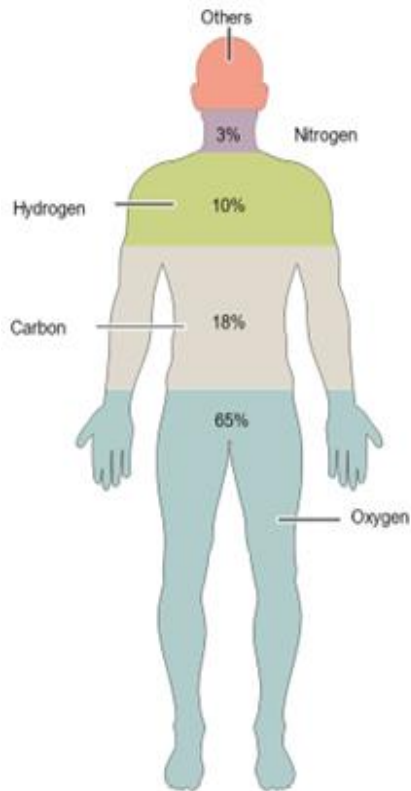
1 H Hydrogen 1.008																	2 He Helium 4.002602
3 Li Lithium 6.94	4 Be Beryllium 9.0121831											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.99840323	10 Ne Neon 20.1797
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305											13 Al Aluminum 26.9815385	14 Si Silicon 28.0855	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.9804	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222
87 Fr Francium 223	88 Ra Radium 226	89 - 103 Actinoids	104 Rf Rutherfordium 261	105 Db Dubnium 268	106 Sg Seaborgium 266	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 268	110 Ds Darmstadtium 269	111 Rg Roentgenium 269	112 Cn Copernicium 285	113 Nh Nihonium 284	114 Fl Flerovium 289	115 Mc Moscovium 288	116 Lv Livermorium 293	117 Ts Tennessine 294	118 Og Oganesson 294



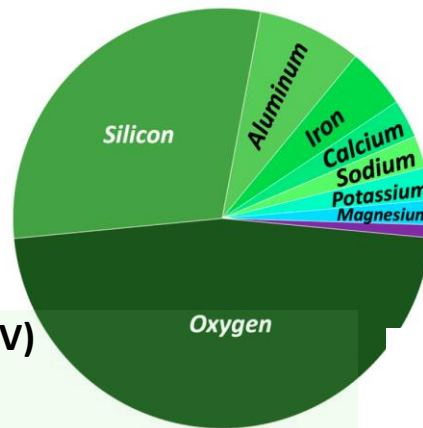
The PHOENIX beamline

57 La Lanthanum 138.9047	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93402	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.967
89 Ac Actinium 227	90 Th Thorium 232.0377	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 260

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**

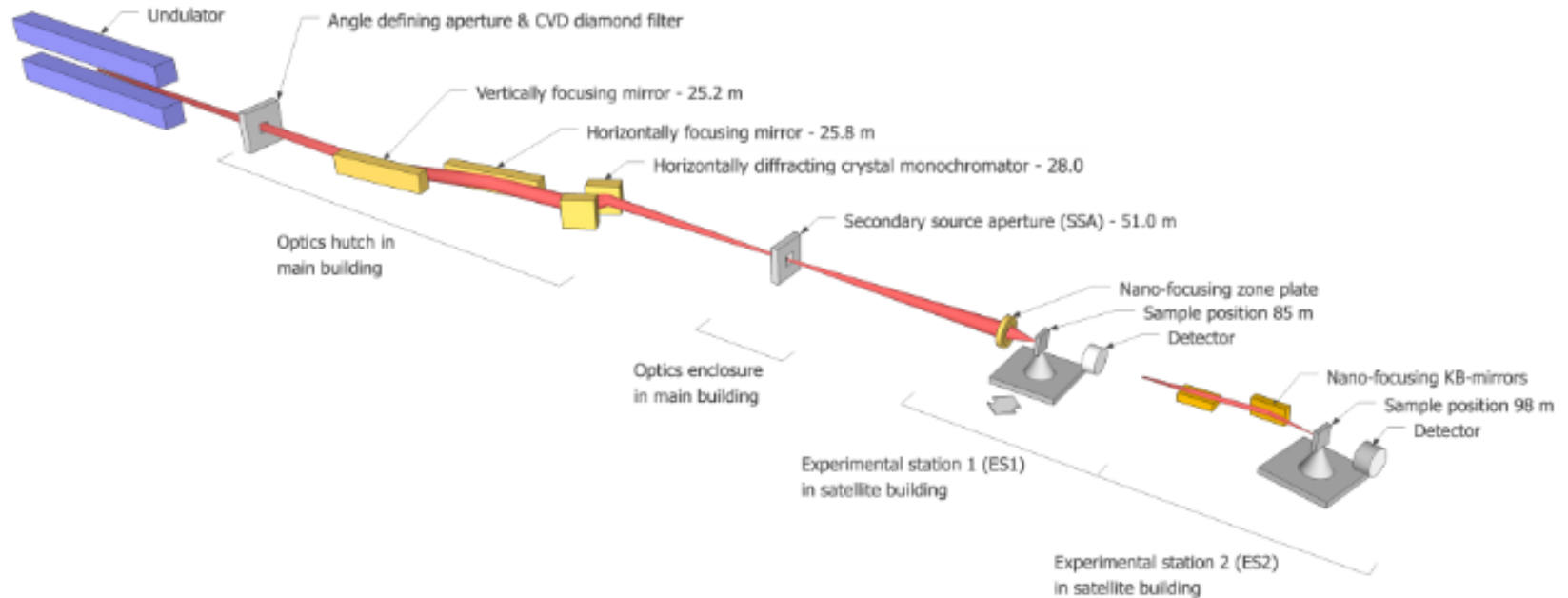
Carbon storage technologies e.g. CaMgCO_3

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

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

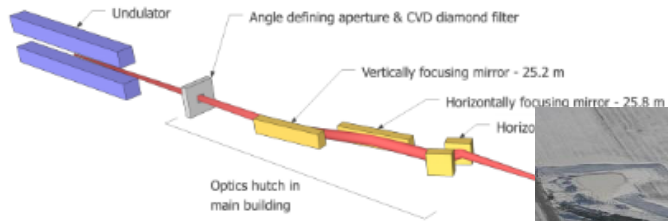
Examples of other beamlines

NanoMAX at MAXIV: 98m long for a small focus



Examples of other beamlines

NanoMAX at MAXIV: 98m long for a small focus

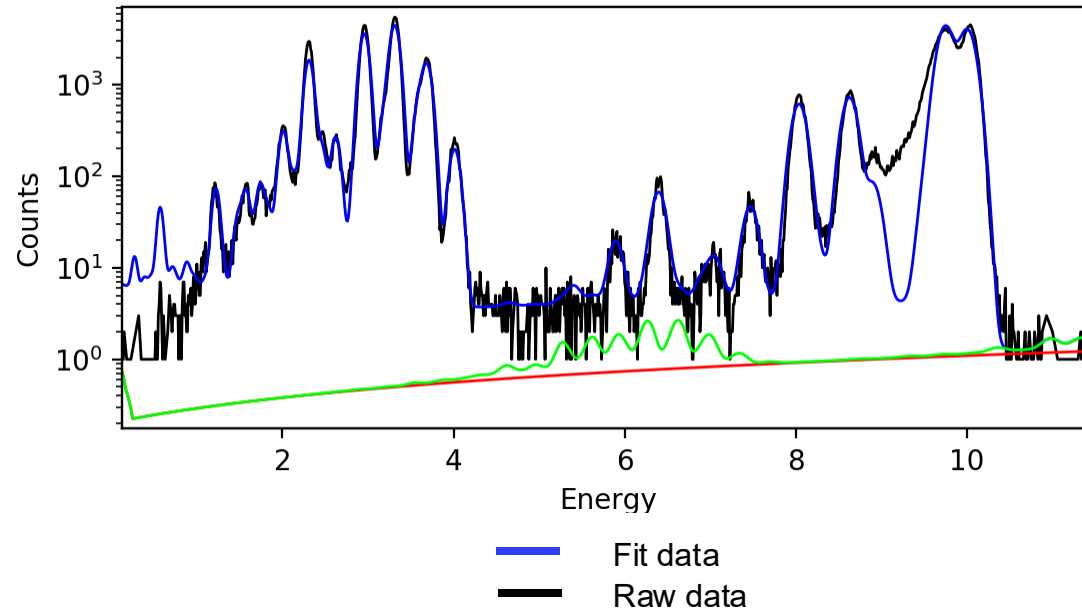


Optics er
in main b

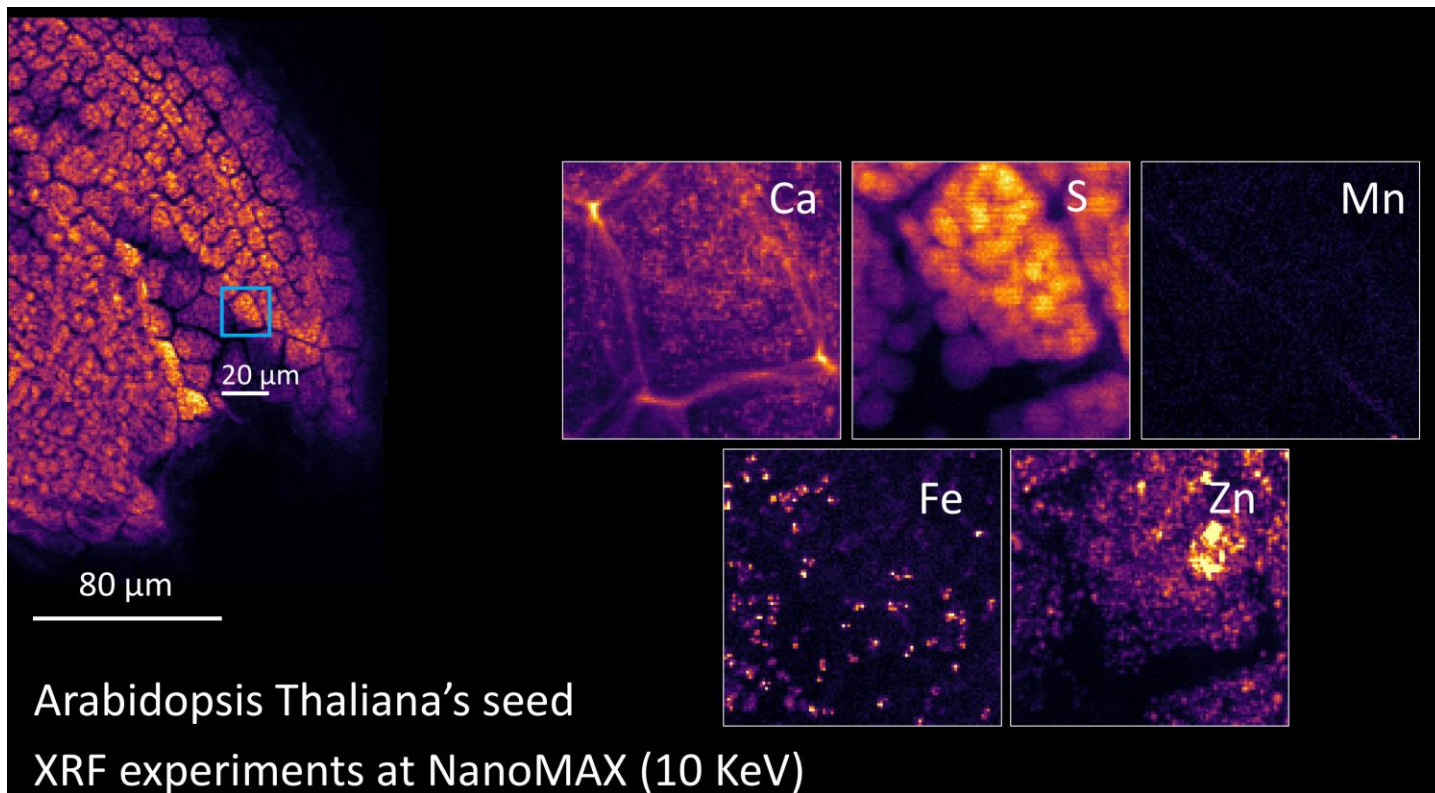


XRF: X-ray fluorescence spectroscopy

XRF experiments at NanoMAX (10 KeV)



XRF: X-ray fluorescence spectroscopy



NanoMAX@MAXIV: 60 nm beamsize at 14keV energy