SOLEX: a tunable monochromatic X-ray source tool for X-ray detectors characterization

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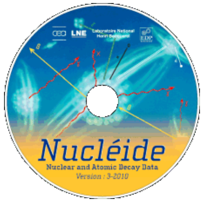
Metrological context

The LNE-LNHB is the French metrology institute for ionizing radiation: One of its missions is to provide accurate radionuclide decay data to the users by:

- accurately measuring photon emission intensities,
- evaluating radionuclide decay data,
- publishing recommended data (Nucleide).



X-ray emission intensities of radionuclides ($P_K\ \omega_K$) [1]

Energy-dispersive (ED) detector efficiency characterization

Need of detector calibration independent from radionuclide decay data

[1] M.M. Bé et al. *Table of radionuclides*, Monographie, BIPM, 2008

Available atomic data and associated uncertainties

All uncertainties are given for one standard deviation

Fe55 → Mn55

	Energy keV	Relative Probability %	Photons per decay x 100	
Kα2	5,88765	51	8,45 ± 0,14	} Kα
Kα1	5,89875	100	16,57 ± 0,27	
Kβ3	6,49045			
Kβ1		20,5	3,4 ± 0,07	Kβ1
Kβ5 "	6,5352			
Kβ5 '				

U = 1.64 %

U = 2.06 %

Table 4. Estimated Percentage Uncertainties for Fluorescence and Coster-Kronig Yields

Z(range)	ω_K	ω_{L_1}	ω_{L_2}	ω_{L_3}	f_{12}	f_{13}	f_{23}
5-10	40-10[a]						
10-20	10-5	>30[a]	>25[a]	>25[a]	10[a]	5[a]	
20-30	5-3	30[a]	25[a,b]	25	15[a]	10[a]	40[a]
30-40	3	30[b]	25	20	15	10	30-20
40-50	2	30-20[b]	25-10	20-10	20[b]	10[b]	20
50-60	2-1	20-15	10	10-5	20	15	20
60-70	1	15	10-5	5	15	10	20-15[a]
70-80	1	15[b]	5	5-3	20[b]	10-5[b]	15
80-90	<1	15	5	3	10	5	15
90-100	<1	15-20	10[b]	3-5	10-50	5-10	15[b]
100-110	1	20	10	5	50-100	15	20

Fluorescence yields : ω

Most of the available experimental data are older than 30 years [2] and measured with less accurate setup than nowadays capabilities

- ω_K uncertainties are larger than 3 % for most elements with Z < 30
- ω_L uncertainties are larger than 15 % for all elements [3,4]

[2] W. Bambynek, *et al. X-ray fluorescence yields, Auger, and Coster-Kronig transition probabilities*. Rev. of Mod. Physics, **44**, (716-813), 1972

[3] M. O. Krause. *Atomic Radiative and Radiationless Yields for K and L Shells*. J. Phys. Chem. Ref. Data, Vol **8**, No 2, 1979

[4] E. Schönfeld, H. Janssen. *Evaluation of atomic shell data.* Nuclear Instruments & Methods in Physics Research A, **369**, (527-533), 1996

[5] M. O. Krause. *Atomic Radiative and Radiationless Yields for K and L Shells*. J. Phys. Chem. Ref. Data, Vol **8**, No 2, 1979

Outline

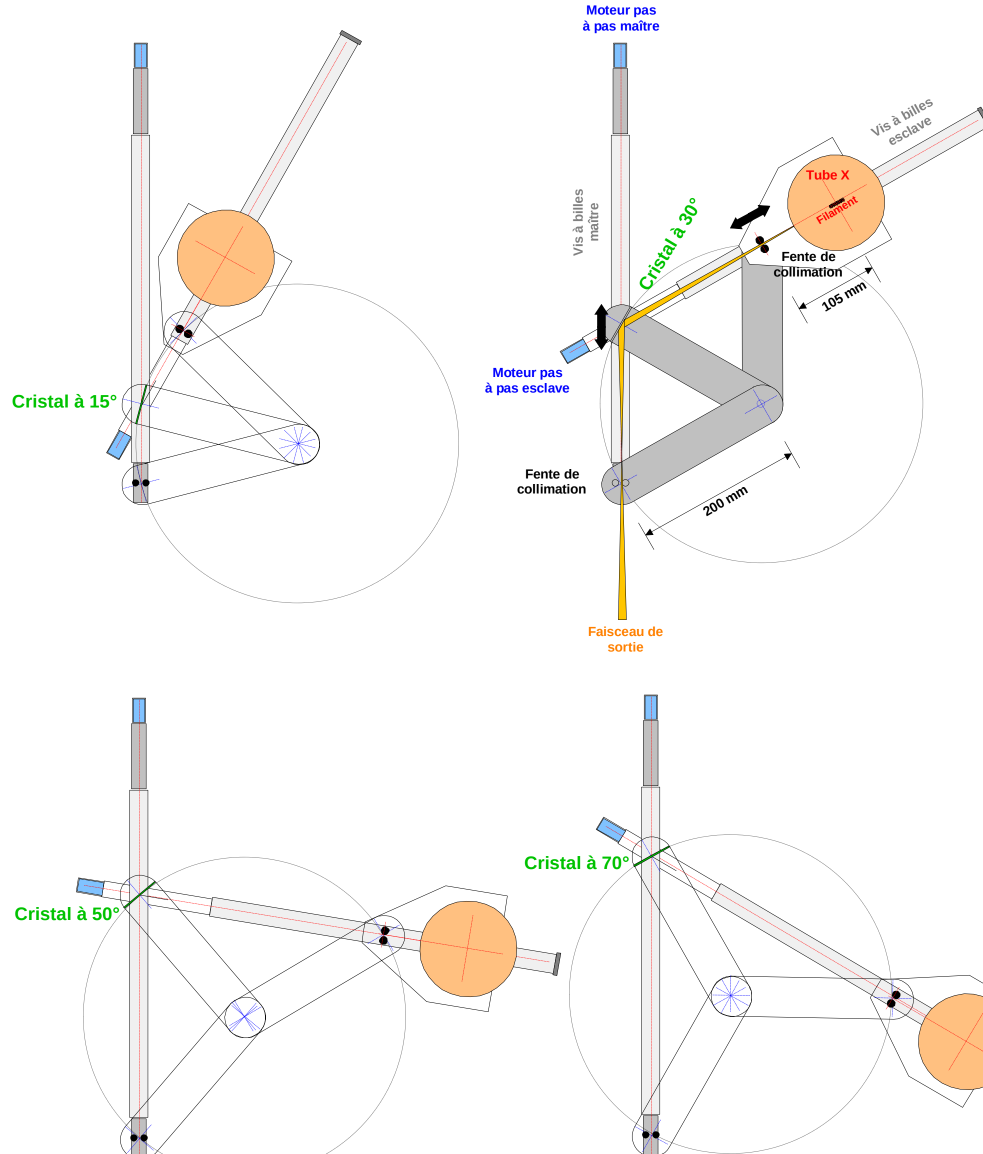
1. SOLEX : The monochromatic & tunable X-ray source
   1.1 The source setup
   1.2 The source technical properties
   1.3 Reference detector

2. Energy-dispersive X-ray spectrometer (EDS) characterization
   2.1 Surface Map
   2.2 EDS response function
   2.3 EDS efficiency calibration

3. Other capabilities of SOLEX
   3.1 Total mass attenuation coefficients measurements
   3.2 Fluorescence yields

1.1 SOLEX, a tunable monochromatic X-ray source: principles

- X-ray tube
- Dispersive cristal
- Johann geometry [6]
- Fixed output: X-ray tube & crystal are moving
- LabVIEW™ interfaced

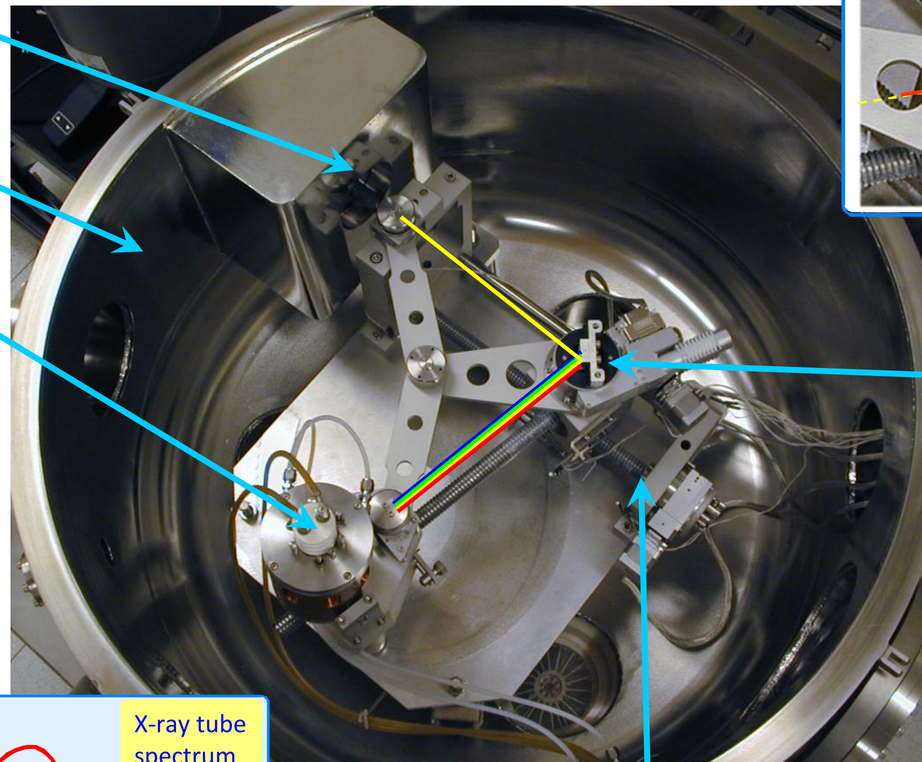


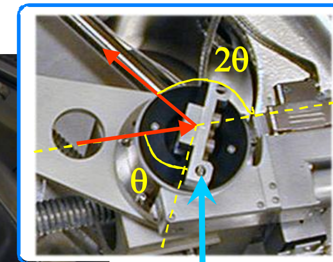
[6] R.E Van Grieken, A.A. Markovicz. *Handbook of X-ray spectrometry, Ed. Dekker, New York*, 1993

1.2 SOLEX: a tunable monochromatic X-ray source [7]

Output 1: X-ray Detector (HPGe, Si(Li), SDD…)

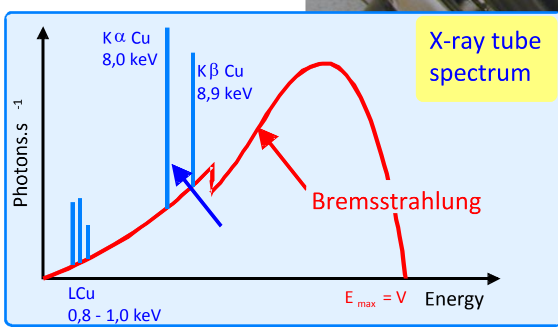
Vacuum chamber (10^{-7} hPa)





X-ray tube

- Windowless, water-cooled
- Several anodes materials : (Cu, Au, Ag Hastelloy…)
- HV up to 50 kV
- Controllable intensity up to 100 mA
- Intensity fluctuations <1%



Dispersive Crystal : Bragg law

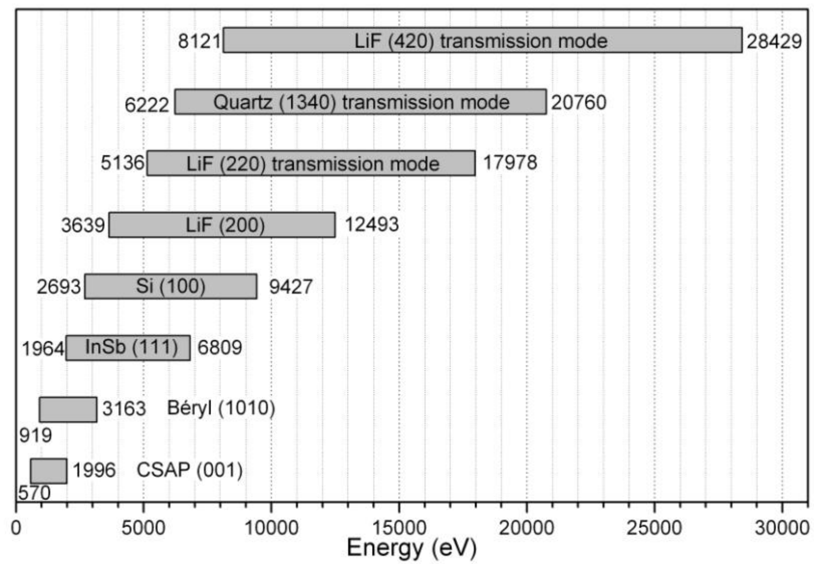
- Emitted X-rays : FWHM ~ some eVs
- Different Crystals (InSb, Beryl, LiF, Quartz…)
- 0.6 keV ≤ E ≤ 28 keV

Options

- Removable filter holder
- Proportional counter for absolute flux measurements

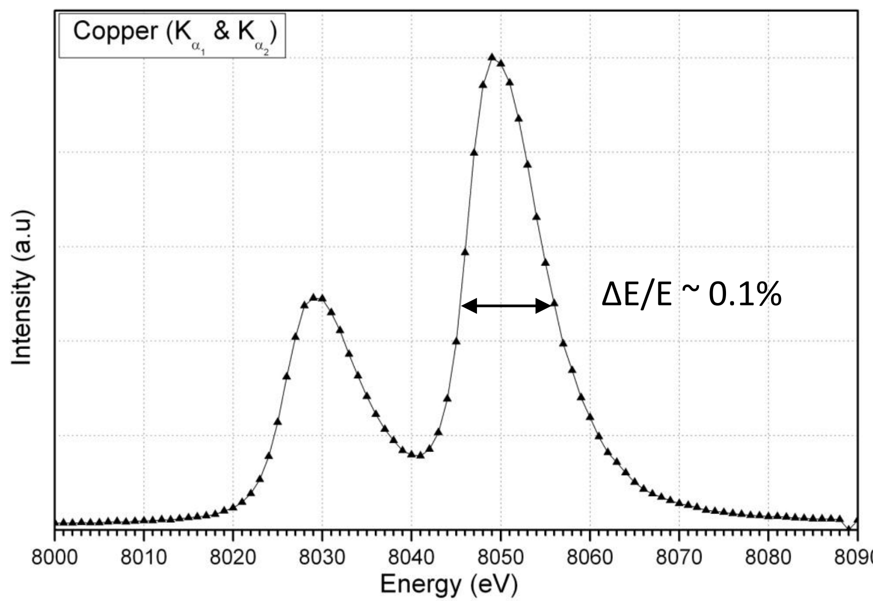
[7] C. Bonnelle, et al. *SOLEX : a tunable monochromatic X-ray source in the 1-20 keV energy range for metrology*. Nuclear Instruments & Methods In Physics Research A, **516**, (594-601), 2004

1.2 SOLEX: characteristics



Worse spectral resolution

Good energy resolution & reproducible energy-calibration

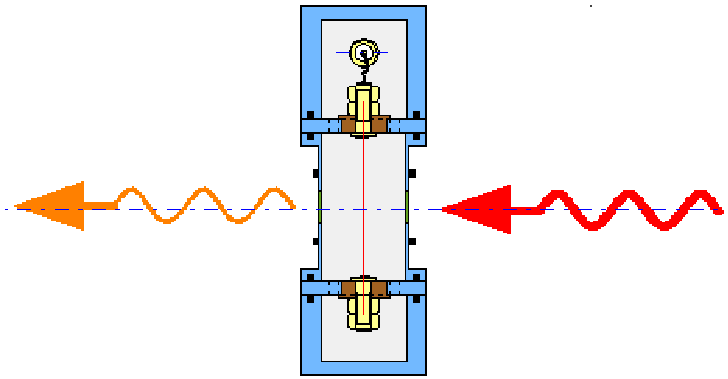


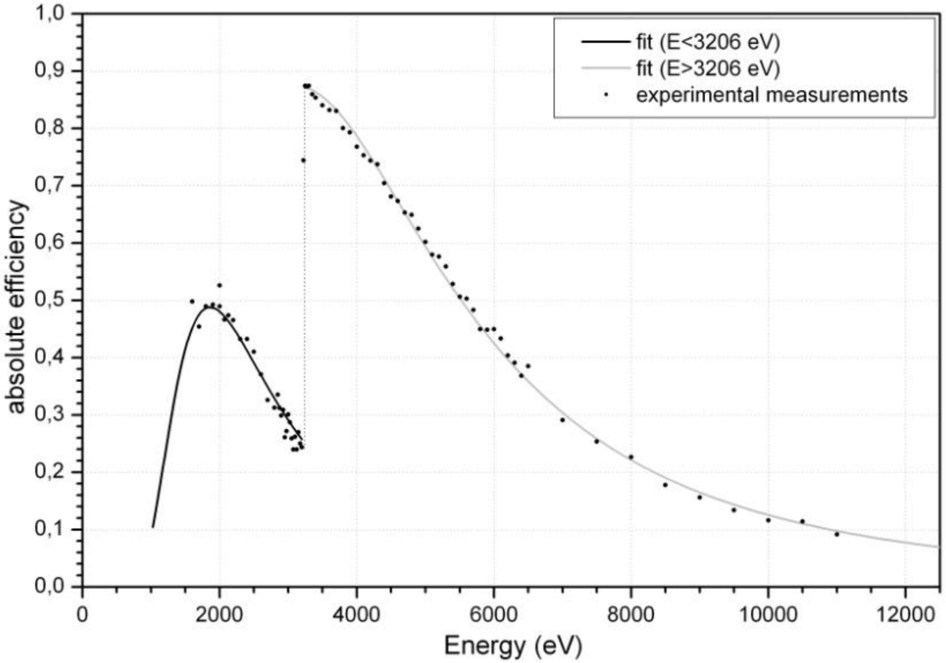
ΔE/E ~ 0.1%

1.3 Gazeous Proportional Counter as reference detector

- Mounted on the 2nd output
- Two beryllium windows
- Full transmission/absorption characterization

- Dedicated to full-energy peak efficiency calibration





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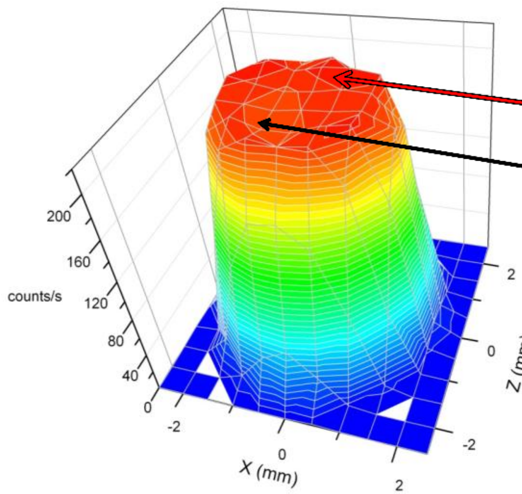
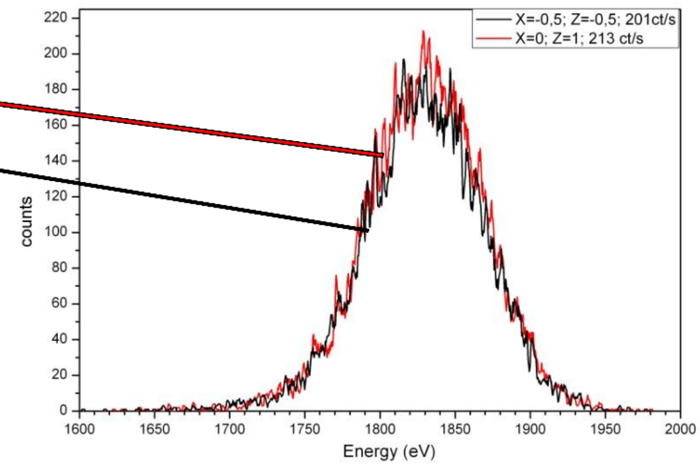
   3.1 Total mass attenuation coefficients measurements
   3.2 Fluorescence yields

2.1 EDS characterization: surface map

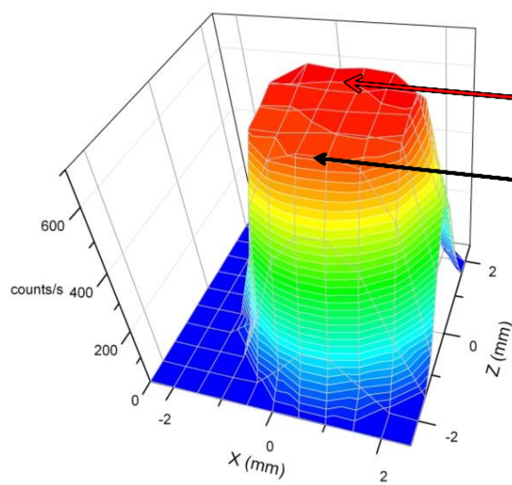
- 2D scan (40 x 40 mm)
- Beam size about 0,5 x 0,5 mm
- Spectrum acquisition and automated treatment

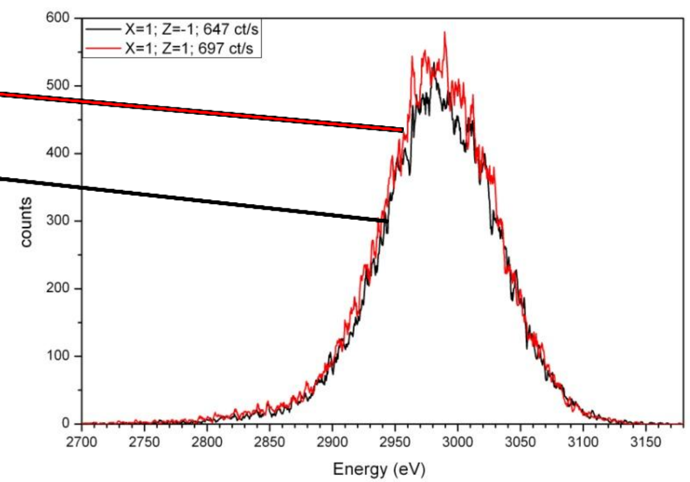
1830 eV





2984 eV

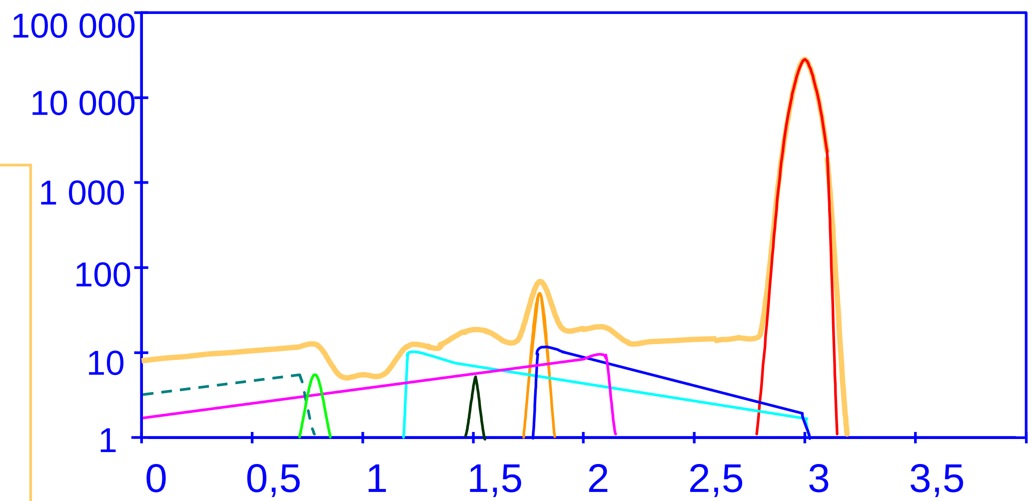


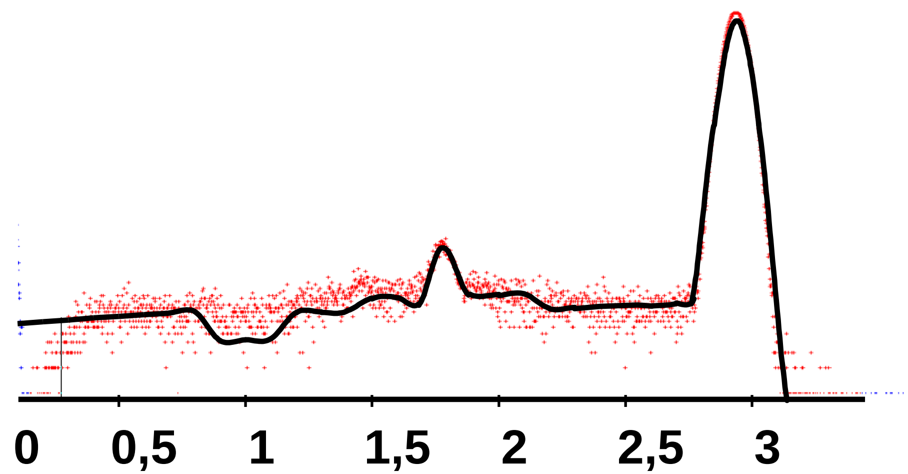


2.2 EDS characterization: response function

Si(Li) EDS
Monochromatic photons
Energy = 3 keV

- Total Spectrum
- Full-energy peak (total absorption)
- Escape peak
- Photoelectrons escape
- Auger electrons escape
- Interaction of Auger electrons of the electrode
- Interaction of photoelectrons of the electrode
- L- fluorescence peak of the electrode
- K- fluorescence peak of aluminum





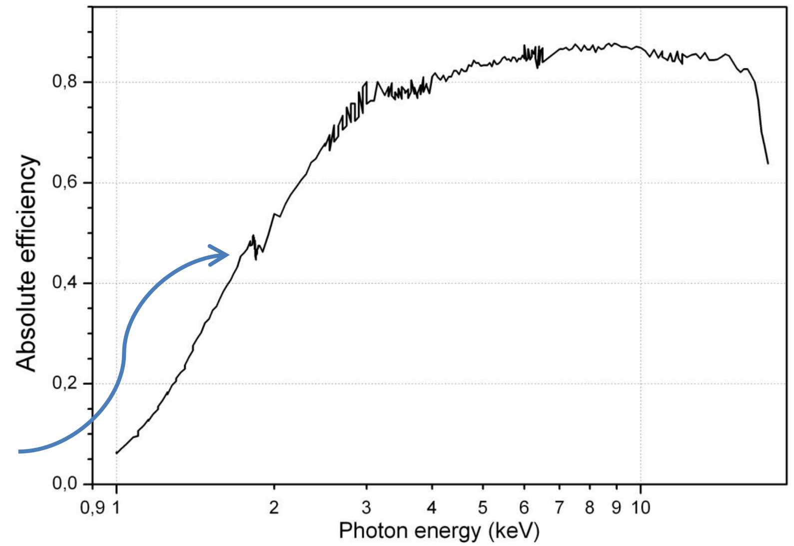
2.3 EDS full-energy peak efficiency calibration

Full-energy peak efficiency of a Si(Li) detector

Comparison with the PC:

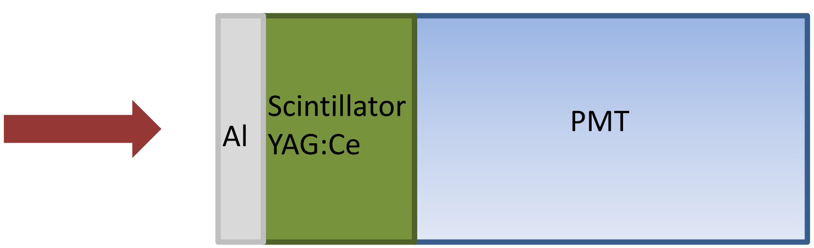
$$\eta_{det} = \frac{N_{det}/N_{PC}}{t_{det}/t_{PC}} \times \eta_{PC}$$

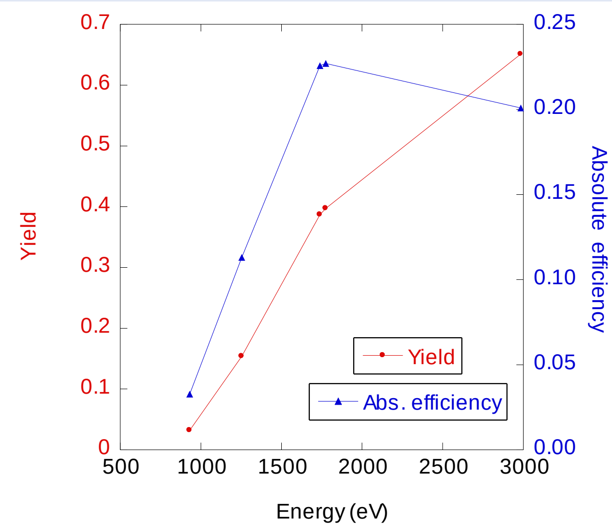
Si K-edge ⇒ dead layer



X-ray counting system based on YAG scintillator and a PM [8]

DUVEX: association of a YAG and a PM

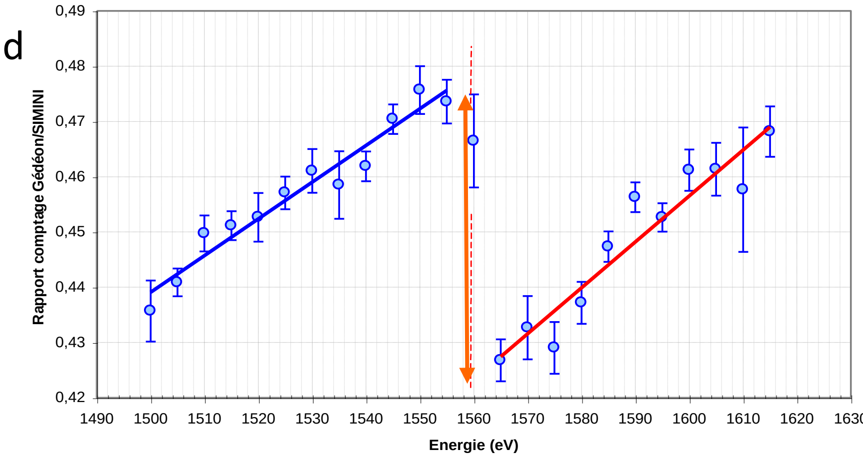


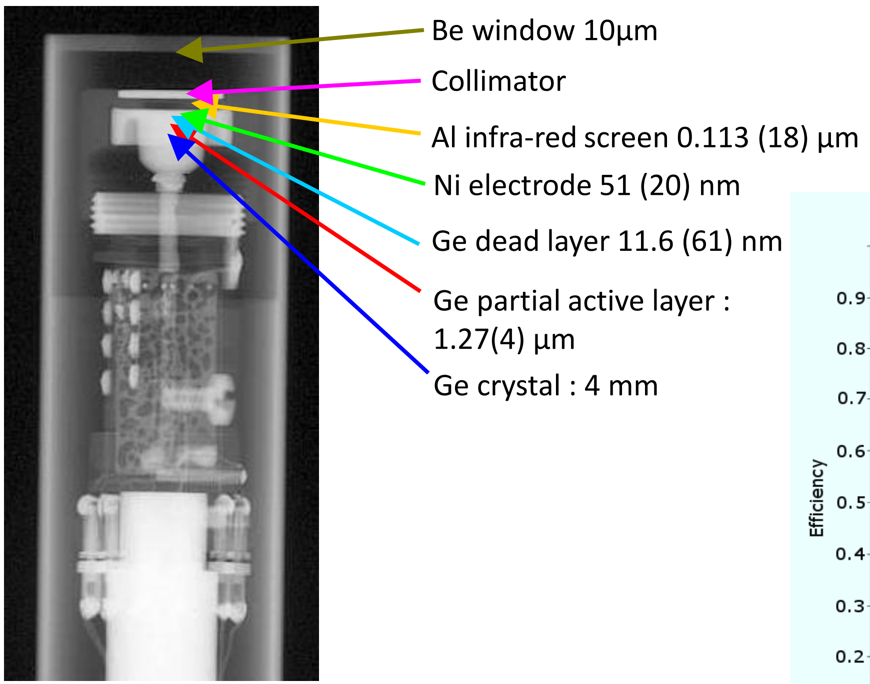


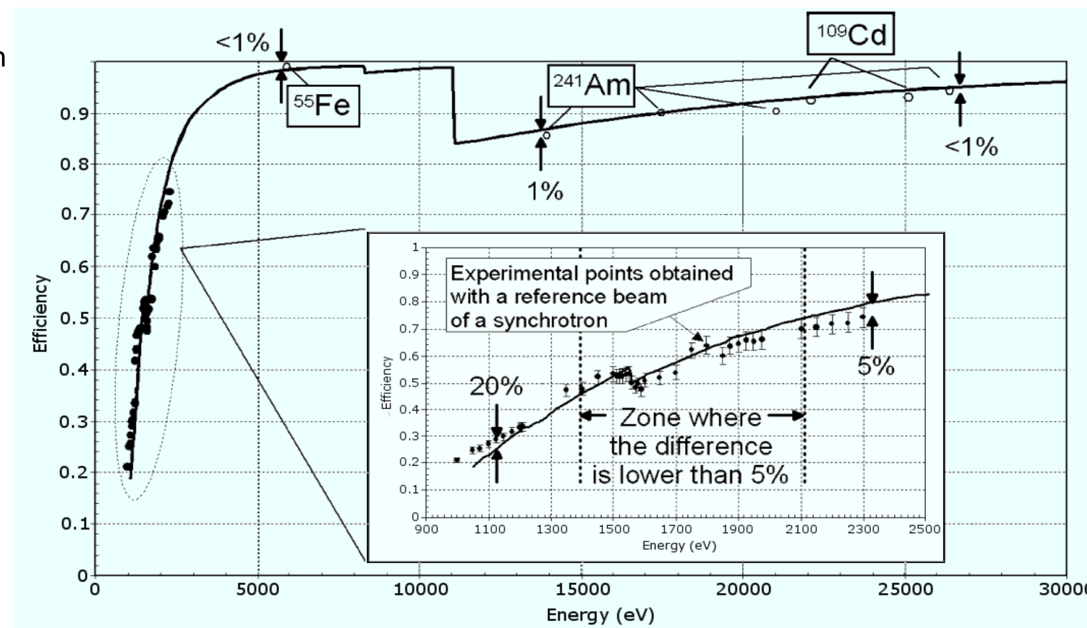
[8] J.M. André, K. Le Guen, P. Jonnard, *DUVEX a versatile EUV-X detector*, **SPIE** Optical Systems Design, Marseille 9/2011, 8167B-81

2.3 EDS full-energy peak efficiency calibration [9]

- Measurement of screen thicknesses : (scanning around the binding energy)
- Germanium partial active layer : peak shape analysis







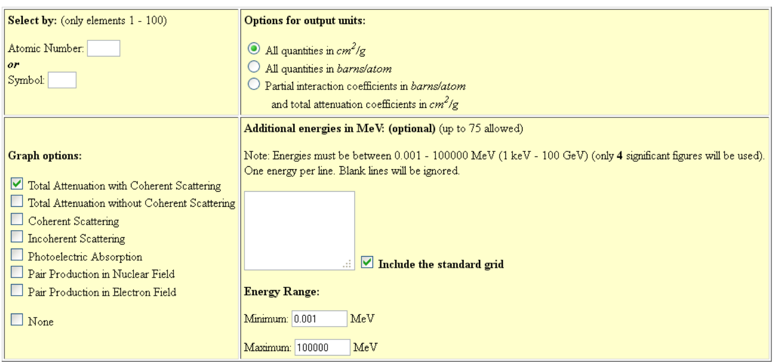
[9] J. Plagnard, et al. *Accurate efficiency calibration of a low-energy HPGe detector using a monochromatic x-ray source*. X-RAY Spectrometry, **36**, (191-198), 2007

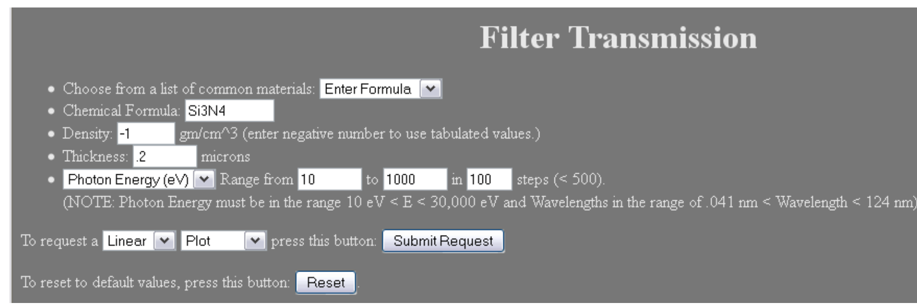
3. Other capabilities of SOLEX

Mass attenuation coefficients measurements / Filter transmission

NIST XCOM database [10]

CXRO database [11]



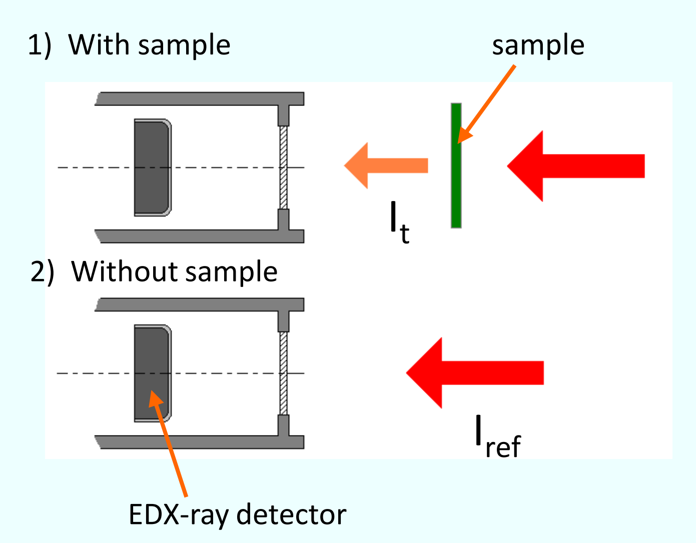


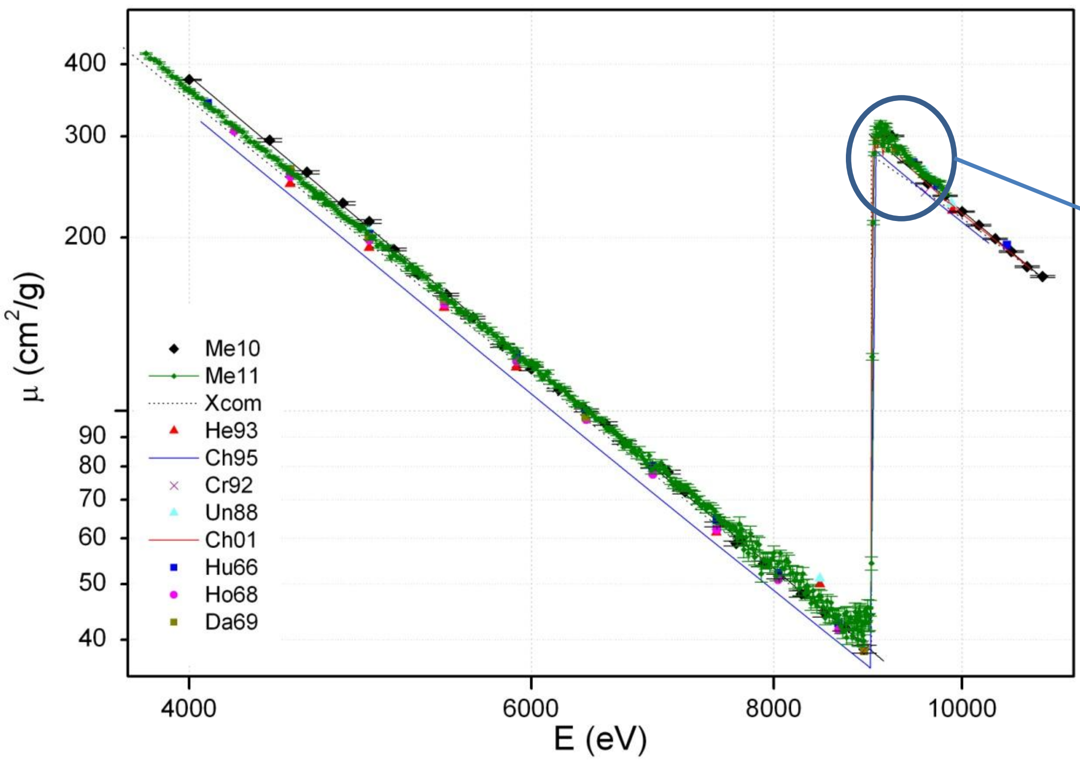
[10] M.J. Berger, J.H. Hubbell, J. Seltzer, S.M. Chang, J.S. Coursey, R. Sukumar, D.S. Zucker, XCOM: Photon Cross Sections Database. Available online: http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html
[11] B.L. Henke, E.M. Gullikson, and J.C. Davis. *X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92*, Atomic Data and Nuclear Data Tables Vol. **54** (no.2), 181-342 (July 1993). Available online: http://henke.lbl.gov/optical_constants/

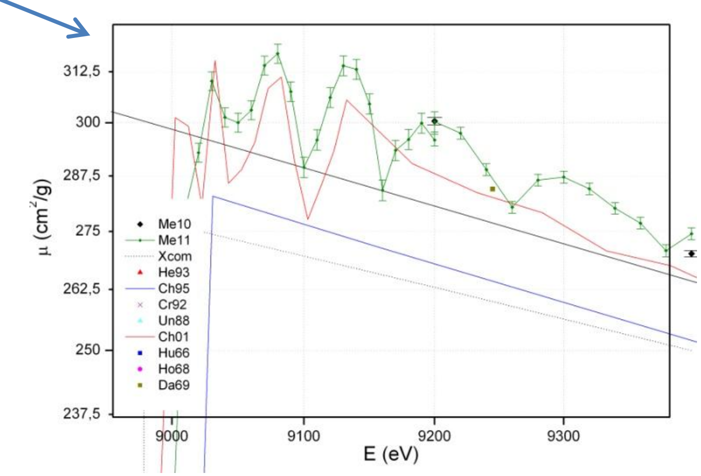
3.1 Total mass attenuation coefficients (example of Cu)

$$\mu/\rho = \tau_{K,L,M...}/\rho + \tau_{cs}/\rho + \tau_{ics}/\rho$$

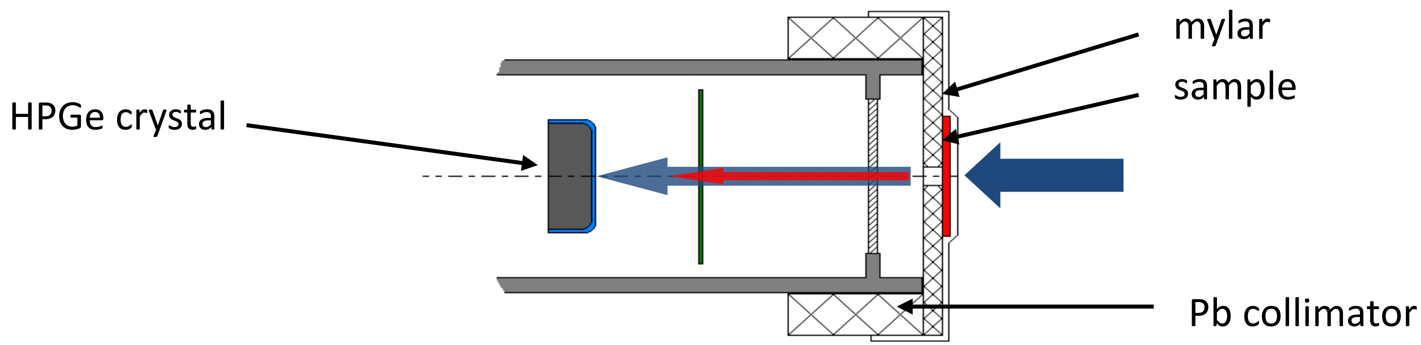
$$\mu/\rho = -\frac{A}{M} \times Ln\left(\frac{I_t}{I_{ref}}\right)$$





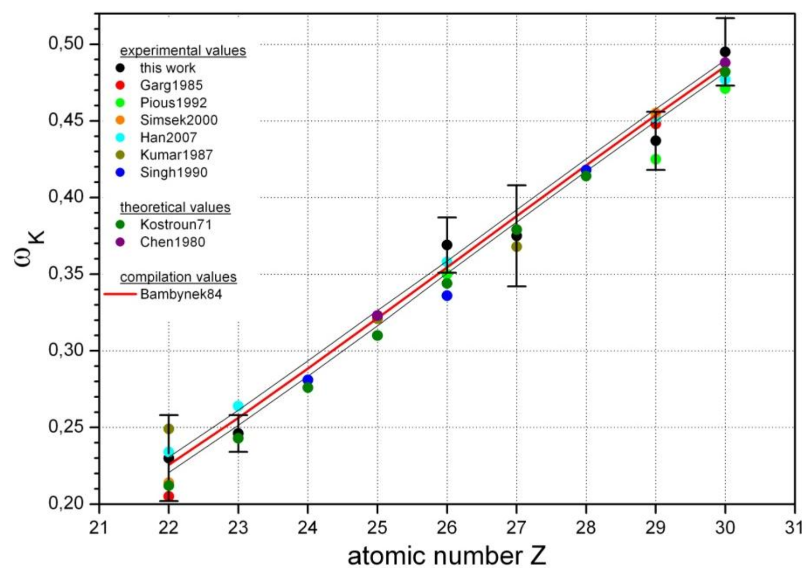


3.2 Fluorescence yields



- Only one solid angle to measure
- Simultaneous measurement of the input beam and the fluorescence lines
- Low input rate

Z	element	$\omega_{K\alpha}$	$\omega_{K\beta}$	ω_K
22	Ti	0.206(23)	0.0233(55)	0.230(28)
23	V	0.219(9)	0.0269(32)	0.246(12)
26	Fe	0.323(16)	0.0452(24)	0.369(18)
27	Co	0.332(29)	0.0427(38)	0.375(33)
29	Cu	0.384(16)	0.0535(30)	0.437(19)
30	Zn	0.427(19)	0.0682(33)	0.495(22)



[12] Y.Ménesguen et al. *Mass attenuation coefficients in the range 3.8<E<11 keV, K fluorescence yield and K_β/K_α relative X-ray emission rate for Ti, V, Fe, Co, Ni, Cu and Zn measured with a tunable monochromatic X-ray source*. Nuclear Instruments & Methods In Physics Research B, 2010

Conclusion

- SOLEX
  - Laboratory tool : permanent access
  - Flexible
  - Easier than synchrotron, however with less flux
- Tool for accurate characterization of detectors in the 1-20 keV energy range
  - Detector response homogeneity (mapping)
  - Detector response function
  - Efficiency calibration (independent of radionuclides decay data)
- Tool for accurate characterization of materials
  - Improved facility (monochromatic photons, EDS, tuneability)
  - Transmission (filters, sample)
  - Attenuation coefficients
  - Fluorescence yields
  - Etc.