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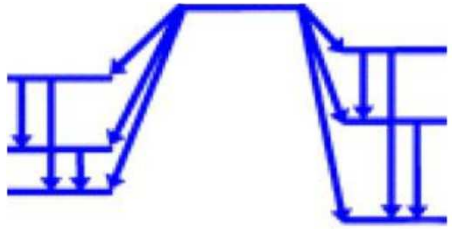


ICRM GSWG

GAMMA-SPECTROMETRY

INTRODUCTION

OUTLINE

General characteristics

Energy resolution

Peak area

Attenuation

Corrective factors

GENERAL CHARACTERISTICS

Gamma-ray spectrometry is a fast and widespread method

- used to identify radionuclides and
- to determine their activity.

- Non-destructive method
- Simple sample preparation
- But relative method (requires calibration using standards)

Mature technique

- Button-push method (which software ?)
- Hidden difficulties / uncertainties factors
- Evolution
  - Large detectors
  - Digital electronics
  - Compton-suppression

GENERAL CHARACTERISTICS

RESULTS DEPENDING ON EQUIPMENT CHARACTERISTICS :

HPGe detector (other detectors for low-energy X-rays (Si(Li), SDD), room temperature detectors NaI(Tl), CdTe, CZT…), etc.)

Sample (material, shape)

Measurement conditions

GAMMA-RAY SPECTRUM

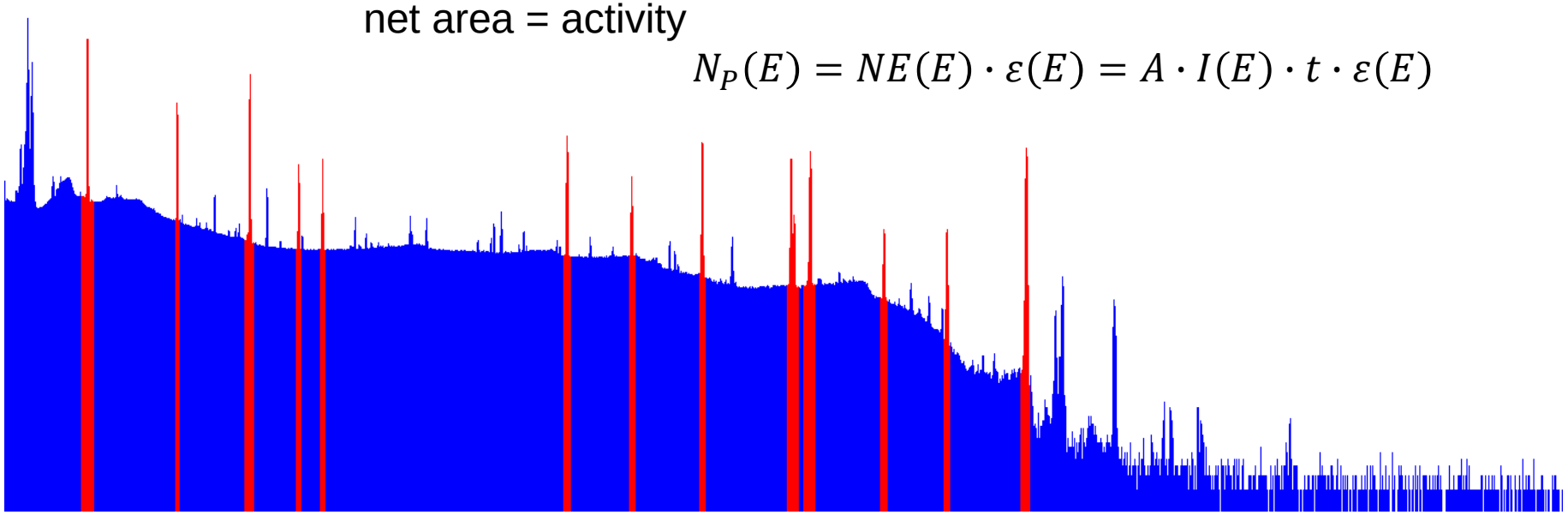
^{152}Eu – Point source at 10 cm from the detector window (100 cm^3) HPGe detector

Peaks (full-energy peaks) :

position = energy -> radionuclide identification;

net area = activity

$$N_P(E) = NE(E) \cdot \varepsilon(E) = A \cdot I(E) \cdot t \cdot \varepsilon(E)$$



Other features (continuum) : partial energy deposition, scattering, escape …

BASIC FORMULA

$$N_P(E) = NE(E) \cdot \varepsilon(E) = A \cdot I(E) \cdot t \cdot \varepsilon(E)$$

or simply: $$n_i = A \cdot I_i \cdot \varepsilon_i$$

A: activity (Bq)

n_i: net peak area

I_i: photon emission intensity

ε_i: detection efficiency

-> 3 results depending on available input parameters:

$$\varepsilon_i = \frac{n_i}{A \cdot I_i} \qquad A = \frac{n_i}{I_i \cdot \varepsilon_i} \qquad I_i = \frac{n_i}{A \cdot \varepsilon_i}$$

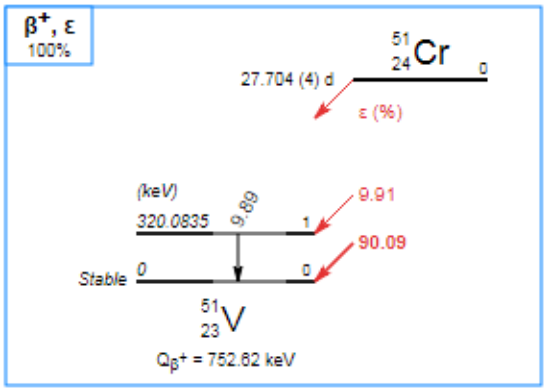
Hidden difficulties : peak area, efficiency for any energy (see “Fitting” section), corrective factors

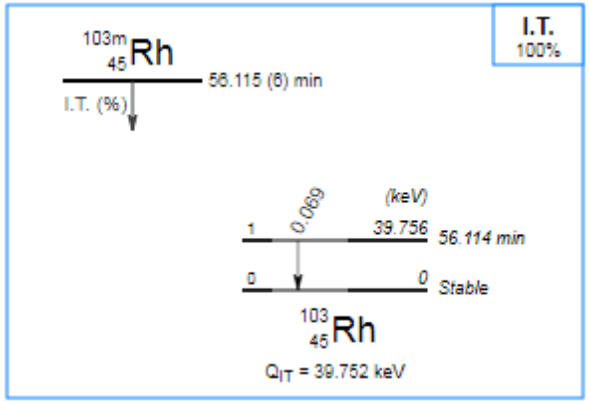
RADIOACTIVE DECAY DATA

- Decay scheme: Difference emission/transition
- Gamma transition = gamma emission + internal conversion

→ $T_g = I_g + I_C$

- Conversion coefficient : $\alpha_T = \frac{I_\gamma}{T_\gamma}$ → $I_\gamma = \frac{T_\gamma}{(1+\alpha_T)}$





^{51}Cr - Tγ = 9.91(2) ; Iγ=9.89 (2)

α_T=0.00181

$$I_\gamma = \frac{T_\gamma}{(1+\alpha_T)} = \frac{9.91}{1.00181} = 9.89$$

^{103m}Rh - Tγ = 100 ; Iγ=0.069 (4)

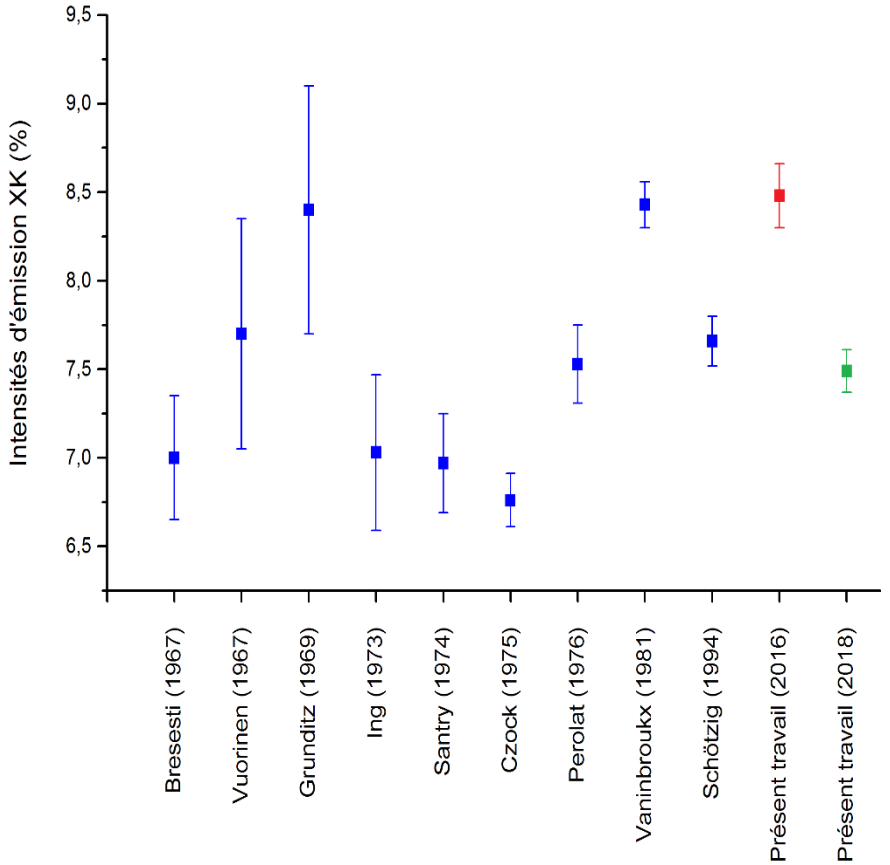
α_T=1448

$$I_\gamma = \frac{T_\gamma}{(1+\alpha_T)} = \frac{100}{1449} = 6.9$$

RADIOACTIVE DECAY DATA

Example:

^{103m}Rh X-ray emission intensities (short half-life)



Difficulty to derive « recommended » data requires carefully detailed information

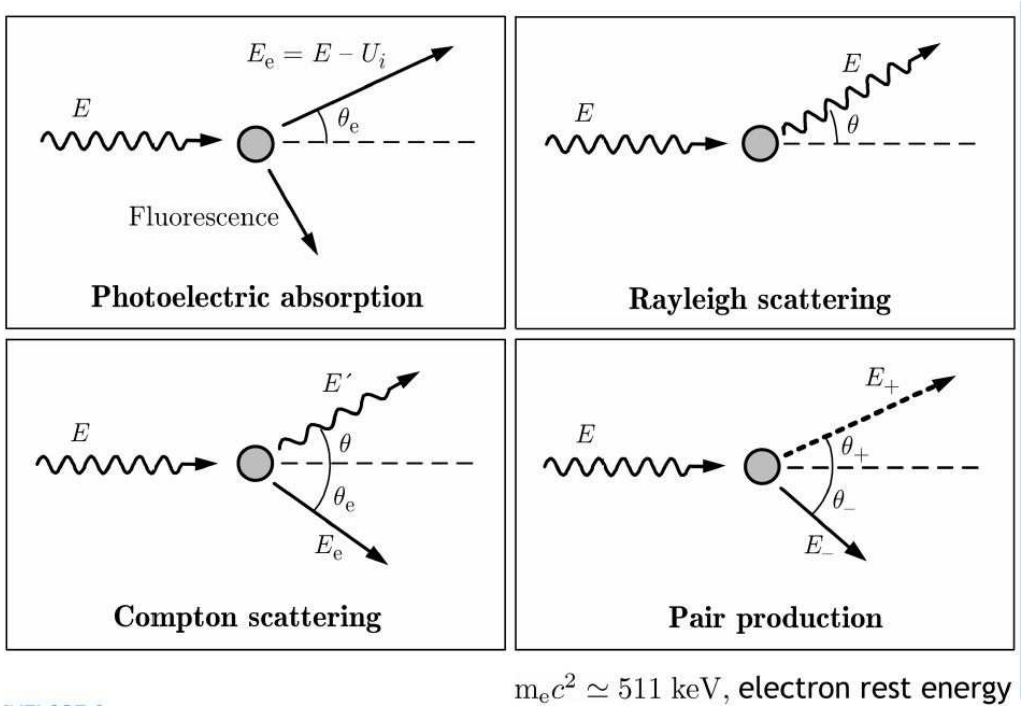
In October 2005, the General Meeting of the *International Committee for Radionuclide Metrology* (ICRM) formally approved the recommendation made by the Nuclear Data Working Group of using the DDEP evaluated decay data in all future nuclear data studies.

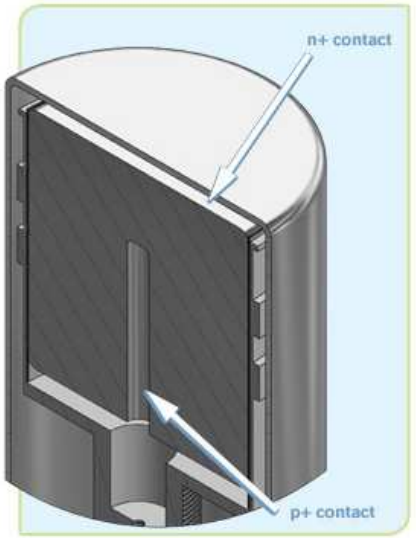
HPGE DETECTOR

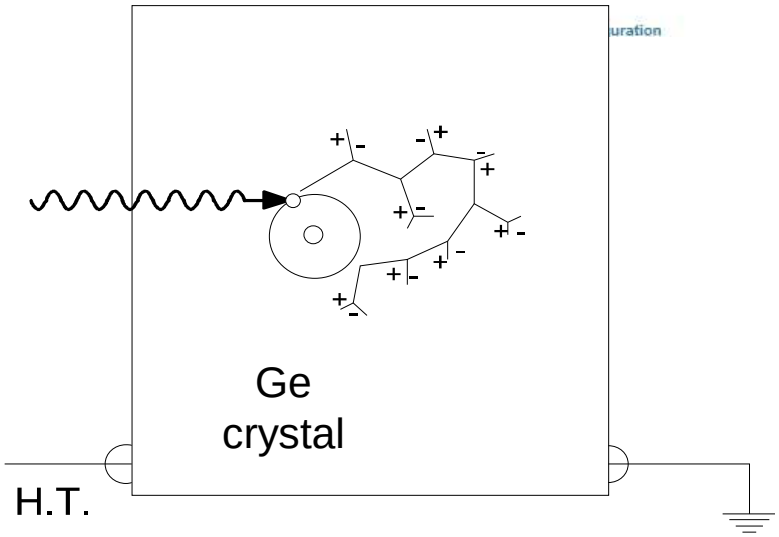
Size -> Efficiency

P or N (low energies)

Photon interaction -> movement of electrons -> electron-hole pairs

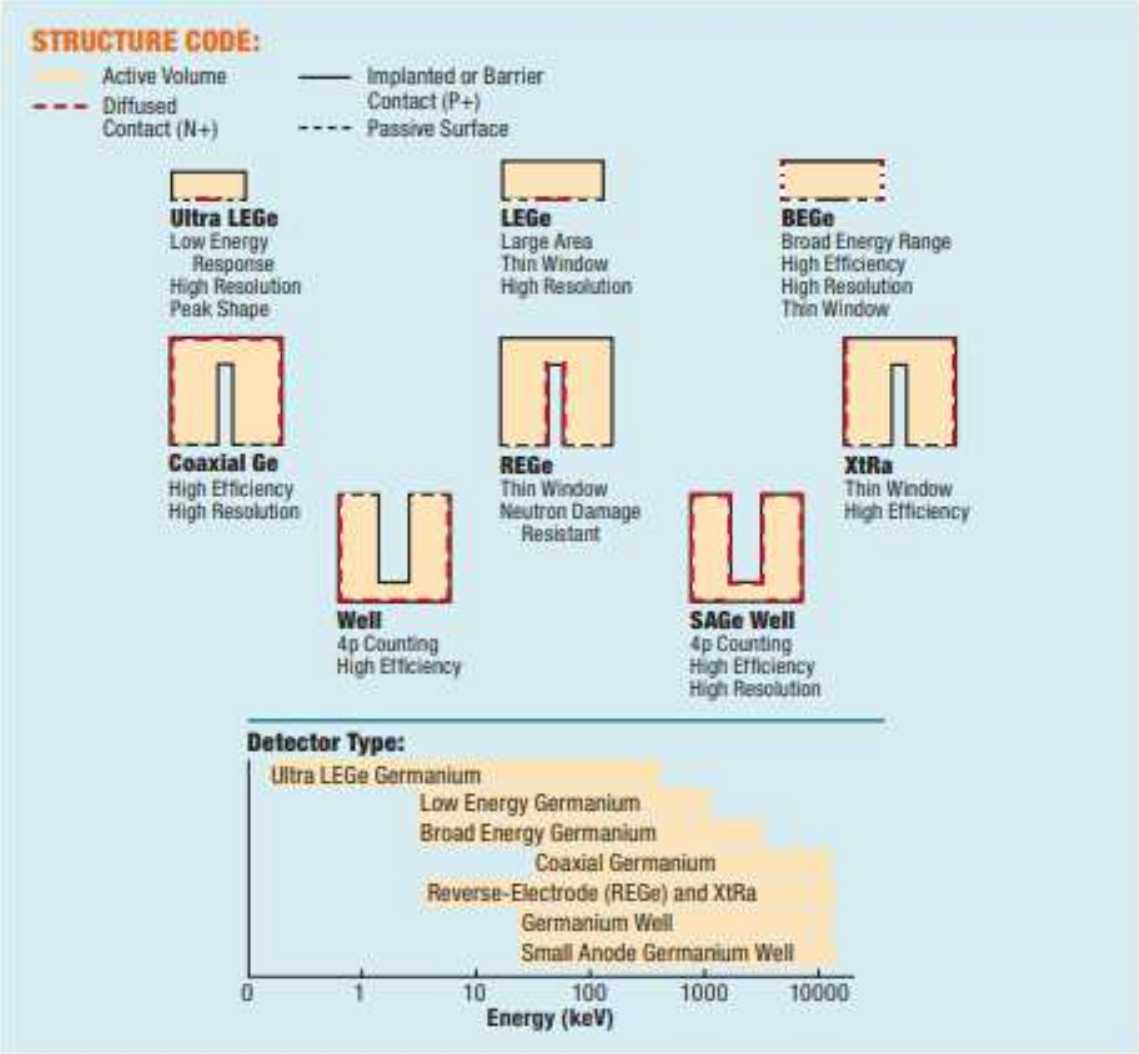






HPGE DETECTOR

Different shapes, types and sizes



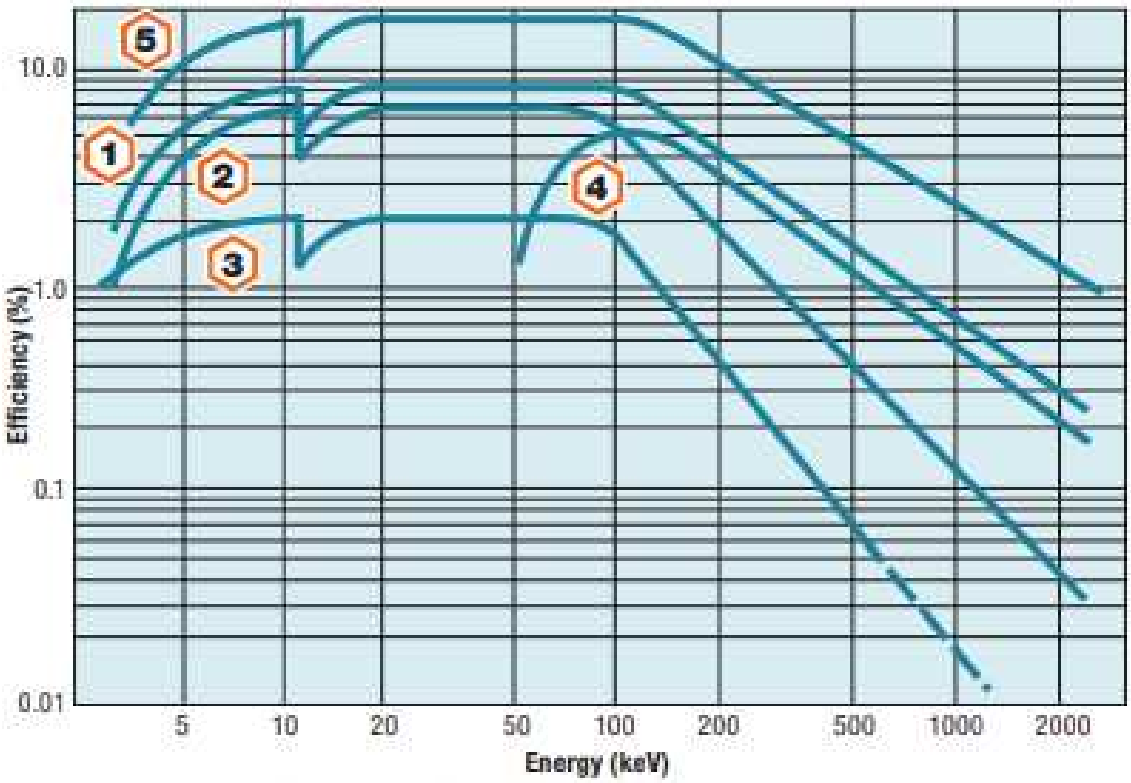
http://www.canberra.com/products/detectors/pdf/Germanium-Det-SS-C39606.pdf

HPGE DETECTOR

Different shapes, types and sizes -> influence on detection efficiency

« Relative efficiency »
compared to 3" X 3" NaI (Tl)

For 1332 keV (^{60}Co at 25 cm)
(FEP efficiency = 1.2 10^{-3})



Typical absolute efficiency curves for various Ge detectors with 2.5 cm source to end-cap spacing

1. REGe, 15% Relative Efficiency XtRa, 15% Relative Efficiency
2. LEGe, 10 cm² x 15 mm thick
3. LEGe, 200 mm² x 10 mm thick
4. Coaxial Ge, 10% Relative Efficiency
5. BEGe, 5000 mm² x 30 mm thick

SPECTROMETRY CHAIN

Detector + electronic modules (analog/digital)

Preamplifier

- RC
- Reset

Amplifier

- Adapt the shape of the pulse – time constant versus count rate

Multi-channel Analyzer

- Number of channels: 10^3 to 1.6 10^4

It is important to characterize the whole spectrometry chain (detector + electronics)

OUTLINE

General characteristics

Energy resolution

Peak area

Attenuation

Corrective factors

ENERGY RESOLUTION

Energy resolution :

ΔE (keV) : FWHM : Full Width at Half Maximum of a peak

- Depends on the energy
- Varies from 0.16 keV (@6 keV) to 2.5 keV (@1,3 MeV), depending on the detector

Resolving power : $\Delta E / E$ (%) : Some 10^{-3}

(5 – 10 % for NaI(Tl))

Characteristic of the spectrometer quality :

- separation of closely spaced peaks
- detection limit

ENERGY RESOLUTION

Initial photon emission : Monoenergetic line (source) (ΔE = some meV)

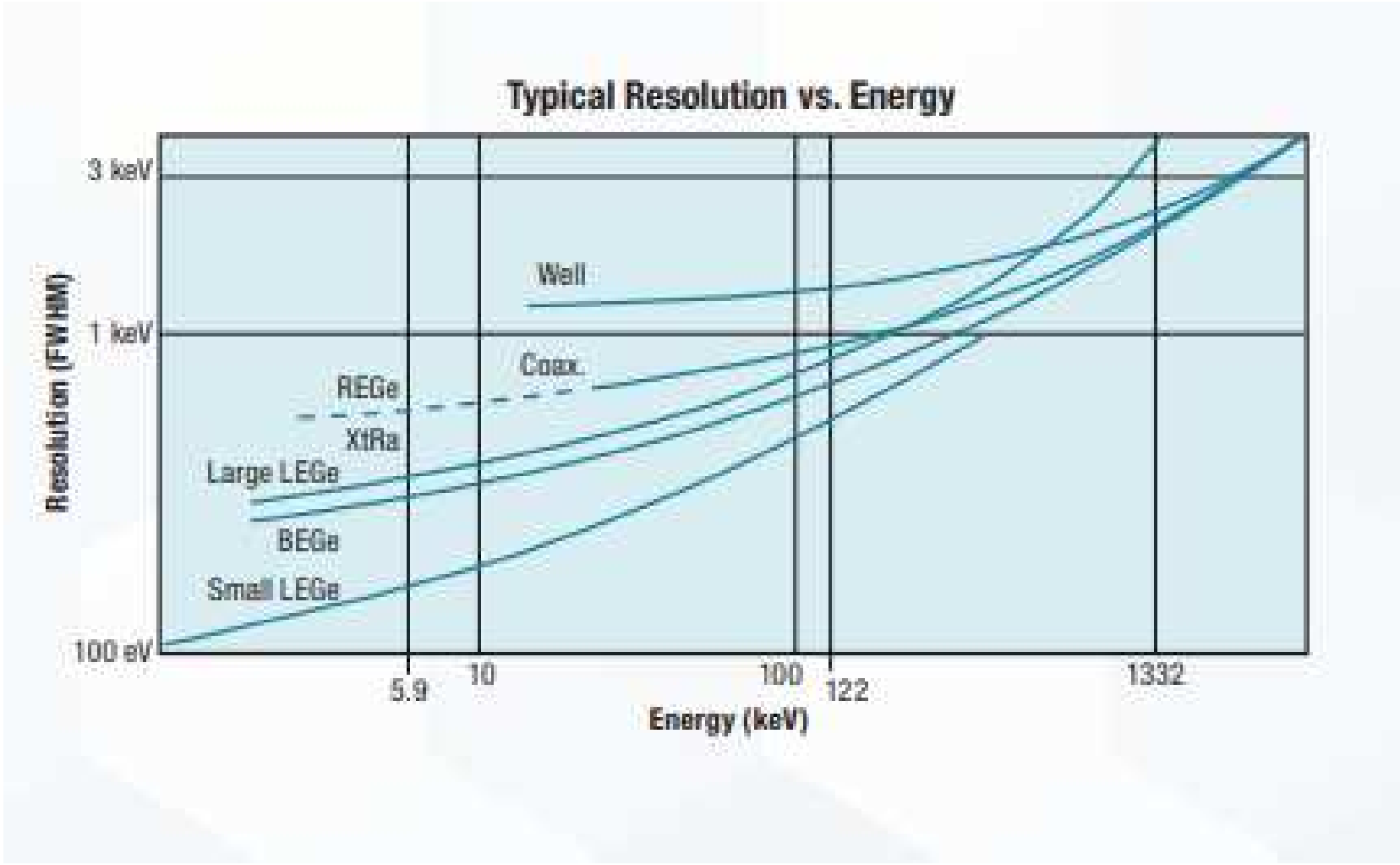
Widening and distortion of the resulting peak (spectrum)

- Widening : Gaussian effects:
  - ✓ fluctuation of the number of charge carriers : ΔE_S
  - ✓ electronic noise : ΔE_E
- Non Gaussian effects:
  - ✓ Charges collection : ΔE_C
  - ✓ Drift of the operating system (detector + electronics)
  - ✓ Pile-up

Result : in the resulting spectrum : 'peak' with finite width (keV) and more or less symmetrical shape

First approximation : Gaussian shape

ENERGY RESOLUTION

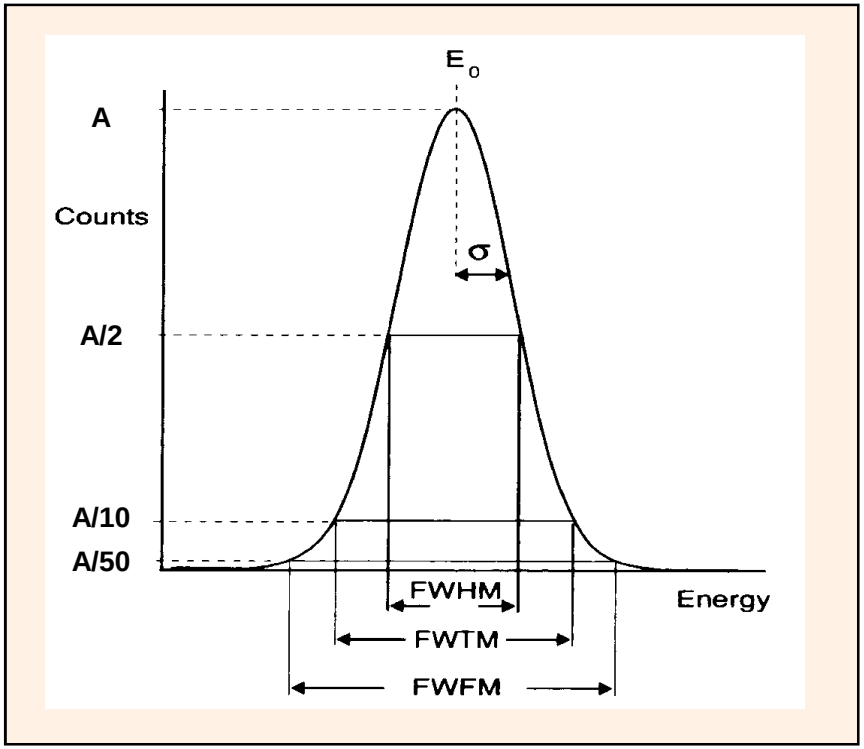


http://www.canberra.com/products/detectors/pdf/Germanium-Det-SS-C39606.pdf

GAUSSIAN DISTRIBUTION

Distribution centered on energy E_0 with standard deviation, σ

Characteristics :



Full width at half maximum of the Gaussian

FWHM (ΔE) = 2,355 σ

Area : $S = (2\pi)^{1/2}\ \sigma\ A$

$$G(E) = A \cdot \exp\left(\frac{(E - E_0)^2}{2\sigma^2}\right.$$

STATISTICAL NOISE : ΔE_S

Cause : fluctuations of the number of charge carriers n

E : incident energy (some keV)
w : mean pair creation energy (some eV)

$$n = \frac{E}{w}$$

Hypothesis : Poisson statistics : $\sigma_n = \sqrt{n}$

Standard deviation of the number of charge carriers

-> Standard deviation of the deposited energy (n w)

$$\sigma_{Es} = w \cdot \sigma_n = w \cdot \sqrt{n} = w \cdot \sqrt{\frac{E}{w}} = \sqrt{w \cdot E}$$

STATISTICAL NOISE : ΔE_S

Example : (at 77K : w = 2.96 eV in Ge
w = 3.76 eV in Si)

E = 1 MeV -> in Ge : n = 3.3 10^5

$$\sigma_{Es} = \sqrt{w \cdot E} = \sqrt{2.96 \cdot 10^6} = 1.72\ keV$$

$$\Delta_{Es} = 2.355 \cdot \sigma_{Es} = 4.05\ keV$$

???

The observed width is much lower (< 2 keV)

-> F = Fano factor : $F = \dfrac{Observed\ variance}{Poisson\ predicted\ variance}$

STATISTICAL NOISE : ΔE_S

$$\Delta_{Es} = 2.355 \cdot \sqrt{F \cdot \sigma_{Es}^2} = 2.355 \cdot \sqrt{F \cdot w \cdot E}$$

Fano factor < 1 (charges creation are not independent : correlations)

Measured for Ge and Si : value depending on the quality of the crystal ?

Experimental values : (increasing versus time …)

Ge : 0.07 to 0.12

Si : 0.08 to 0.12

ELECTRONICAL NOISE : ΔE_E

Preamplifier – amplifier

- Independent on the energy
- Can be determined using a pulser : input at the preamplifier « test »

CHARGE COLLECTION : ΔE_C

Causes : trapping of charge carriers and ballistic deficit

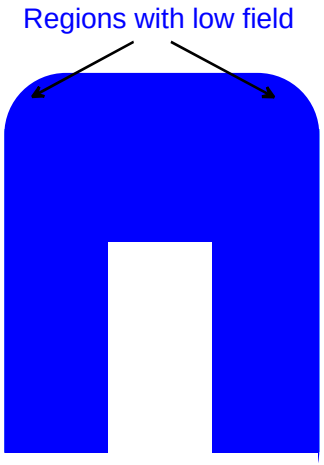
Trapping (impurities or crystal imperfections) : loss of charge or slowing of the rate of charge collection

Ballistic deficit (electron-hole mobility (15% difference in Ge)

Depends on the quality of the crystal and on the electric field (position of the interaction in the detector)

Consequence of the loss of charge :

Low-energy tailing



Improvement :

Increasing the voltage (recommended value by supplier)

Rejecting pulses with slow rise-time

Using collimator to avoid interaction in low electric field regions (front corners)

PEAK FULL WIDTH AT HALF MAXIMUM

$$\Delta E^2 = \Delta E_S^2(E) + \Delta E_C^2 + \Delta E_E^2$$

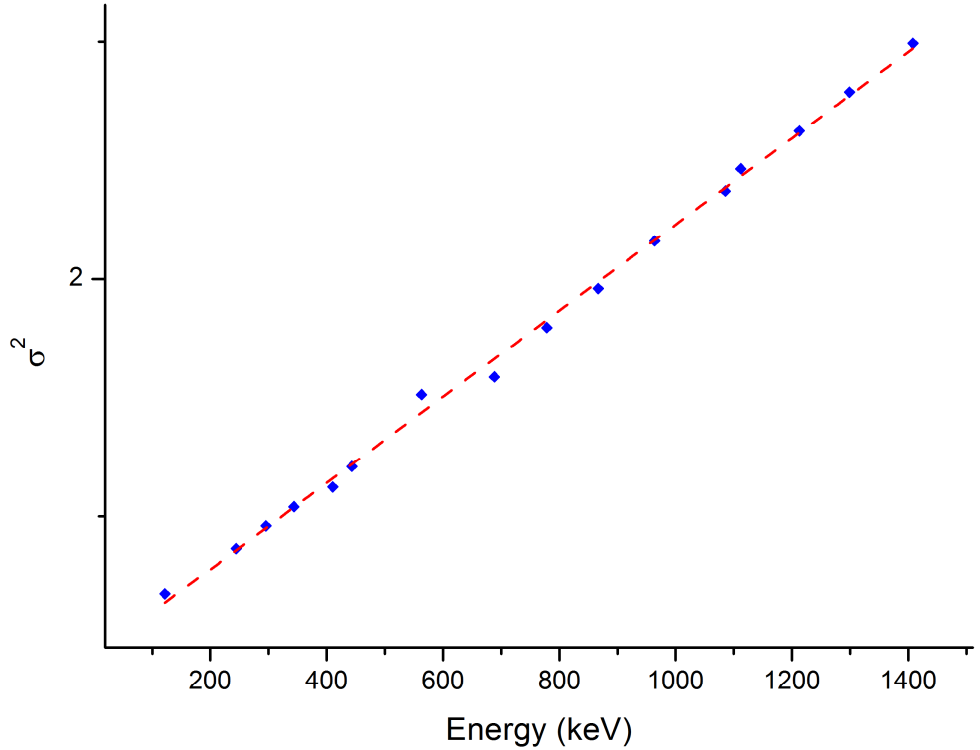
ΔE_S = statistical noise (dependent on the energy)
ΔE_C = charge collection
ΔE_E = electronical noise

First approximation : $\Delta E^2 = K + \Delta E_S^2(E)$

$$\Delta E^2 = K + 2.355^2(F \cdot w \cdot E)$$

FWHM versus the energy

$$\Delta E^2 = K + 2.355^2 (F \cdot w \cdot E)$$



Linear fitting : $FWHM^2 = 0.00182E + 0.4141$
K = 0.414 keV (electronics + charge collection)

$(2.355)^2$ F w = 0.00182 -> F = 0.110

OTHER PEAK SHAPE CHARACTERISTICS

FWTM (Full Width at Tenth Maximum)

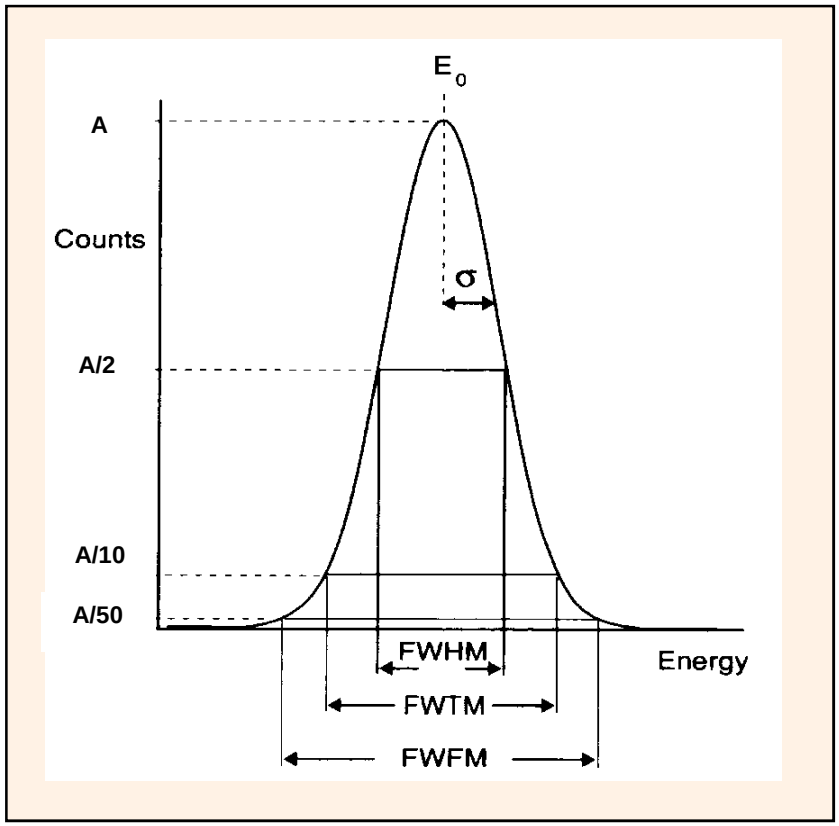
FWFM (Full Width at Fiftieth Maximum)

These values can be compared to those characteristic of a Gaussian (ideal ?) peak :

FWTM / FWHM = 1.82

FWFM / FWHM = 2.38

Information about the peak shape, particularly on its base (collection defects)



OUTLINE

General characteristics

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Peak area

Attenuation

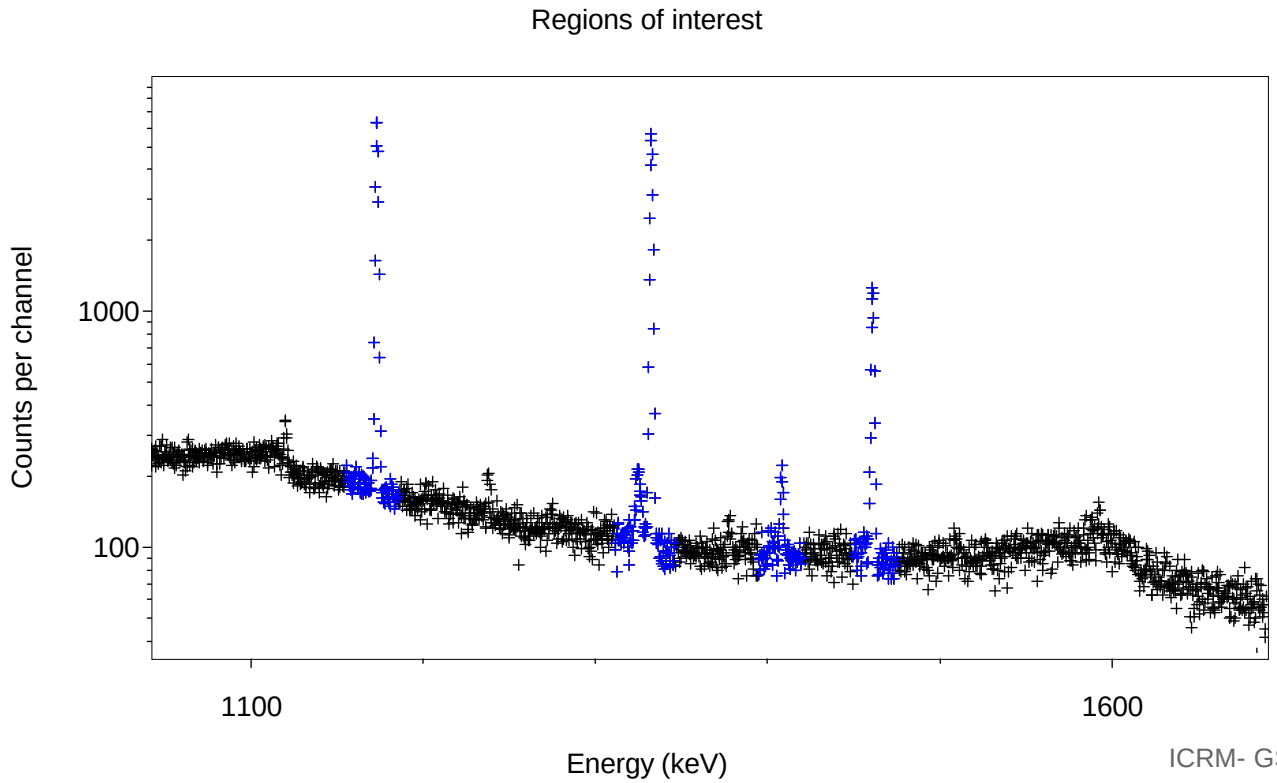
Corrective factors

REGION OF INTEREST

For quantitative analysis : determination of N(E) = peak area

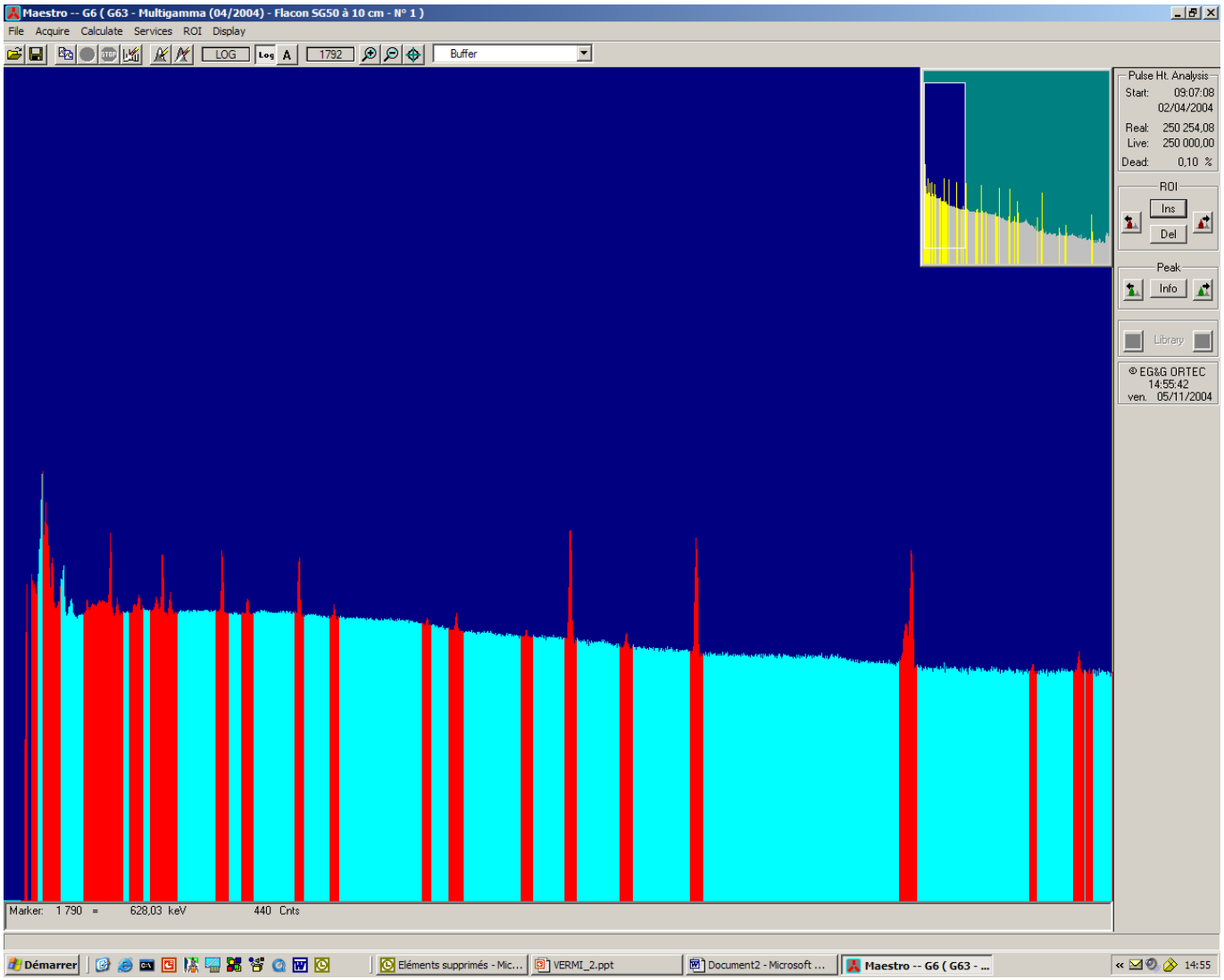
(number of photons with energy E that deposited all their energy in the detector)

Spectrum - > "Regions Of Interest" (ROI's) containing one or several peaks



FINDING PEAKS IN SPECTRUM

Automatic peak search

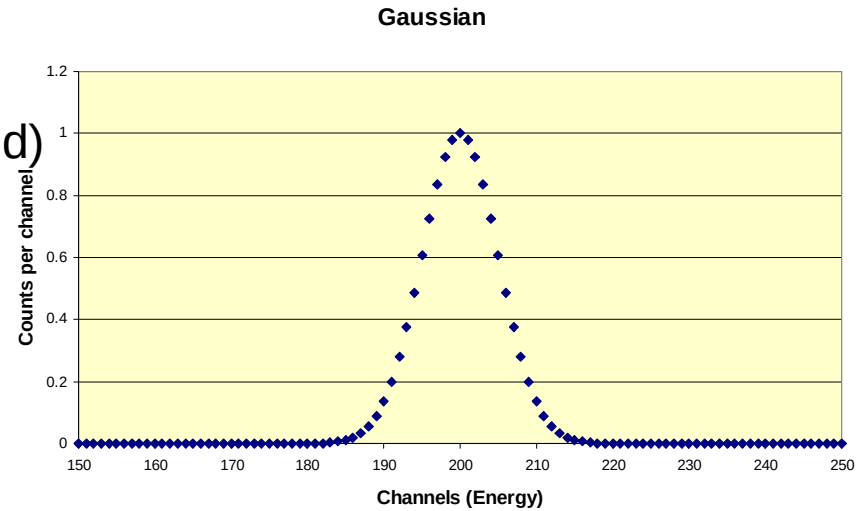


AUTOMATIC PEAK SEARCH

Peak region :

Y (E) = G (E) + (aE + b)

(Gaussian + linear background)



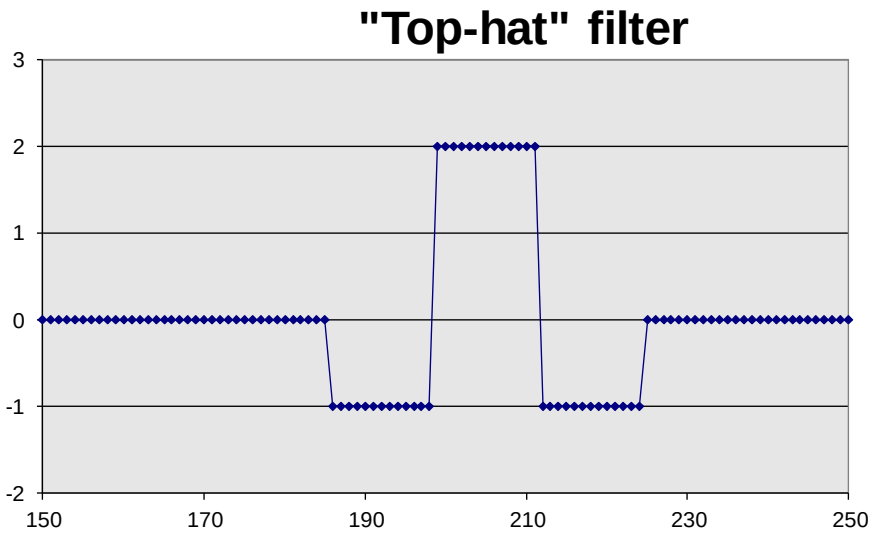
Convolution by a « top-hat » filter

With zero area

Width = Gaussian width

(requires resolution calibration)

$$Y^C = Y \otimes TF$$



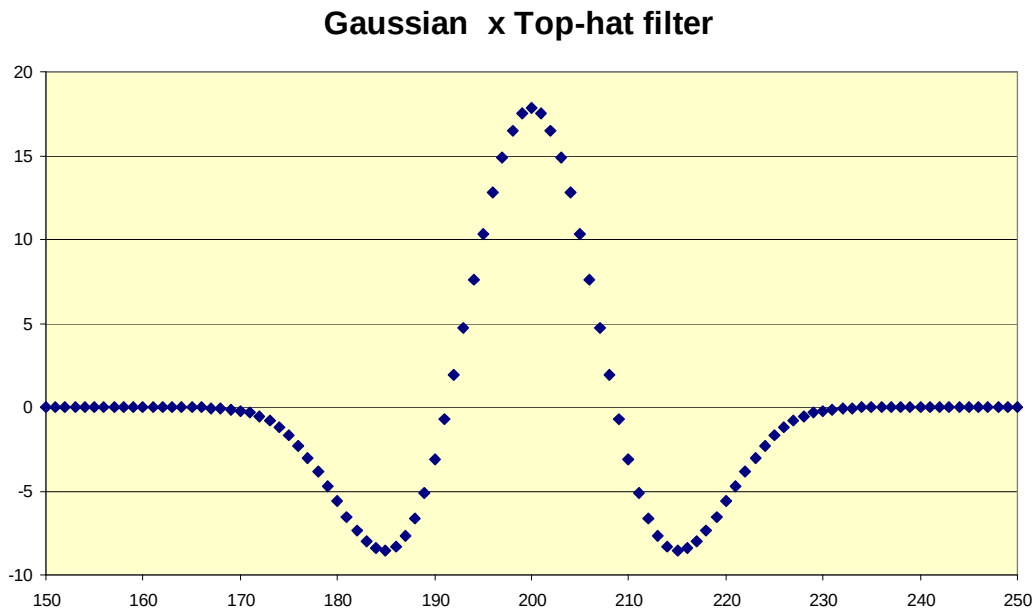
AUTOMATIC PEAK SEARCH

- Presence of a peak when

  $Y^C > T$ (threshold)

Peak FWHM <-> channels where $Y^C = 0$

-> definition of a ROI



Peak detection sensitivity is dependent on the threshold value :

T too low -> spurious peaks

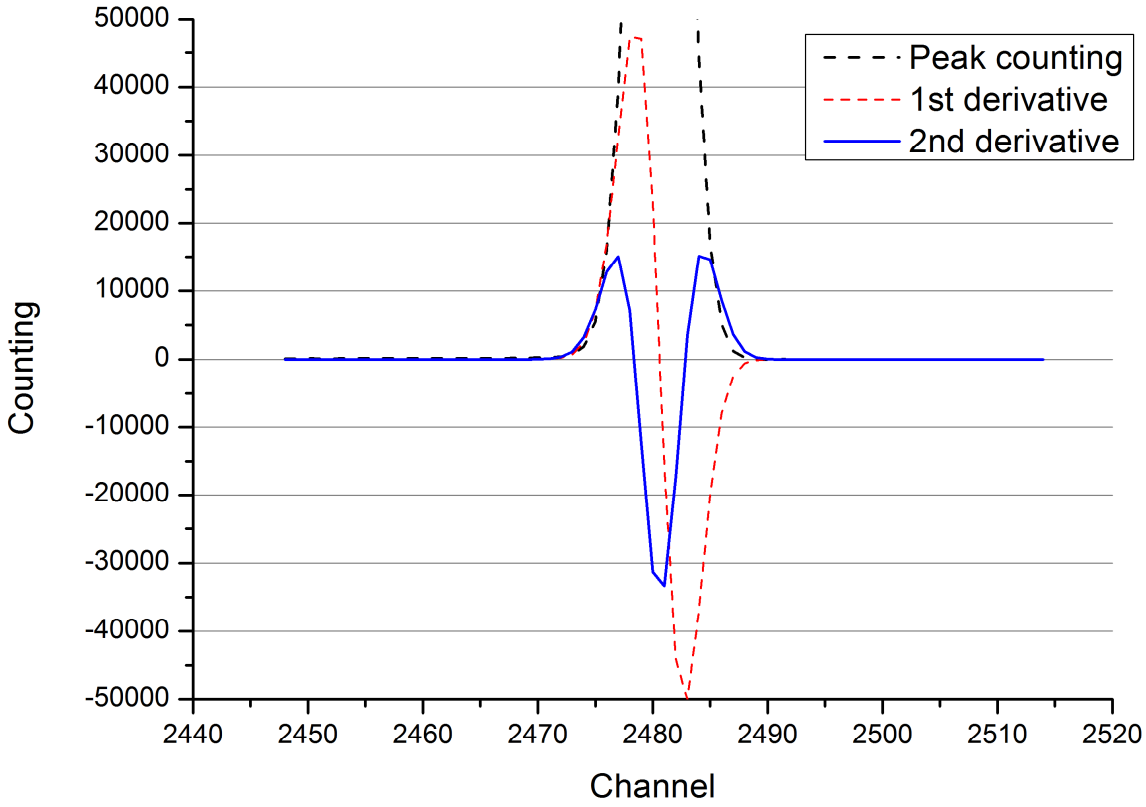
T too high -> missing peaks

AUTOMATIC PEAK SEARCH

DERIVATIVES

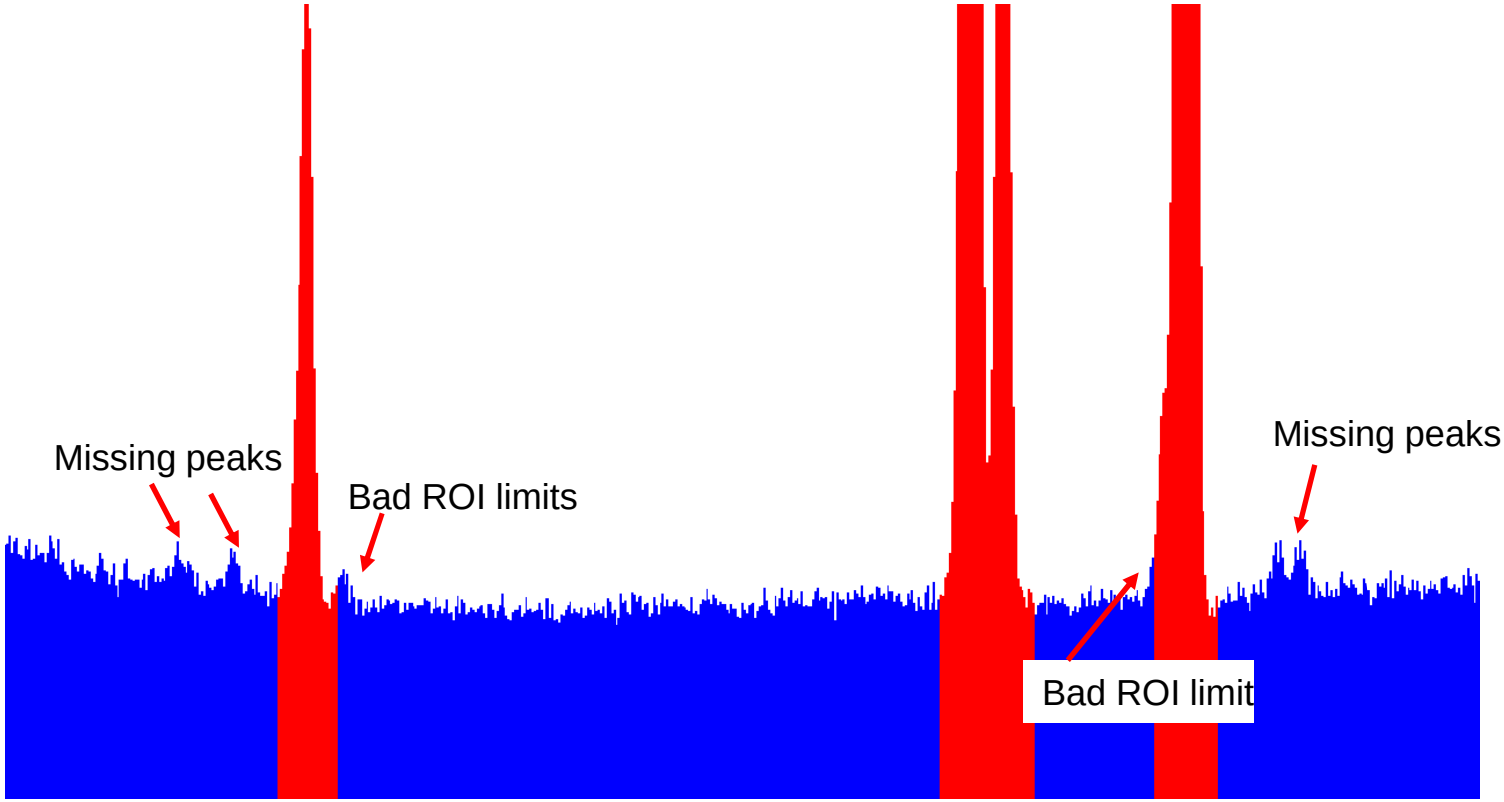
First derivative : change of sign at the maximum peak position

Seconde derivative : negative minimum at the position peak



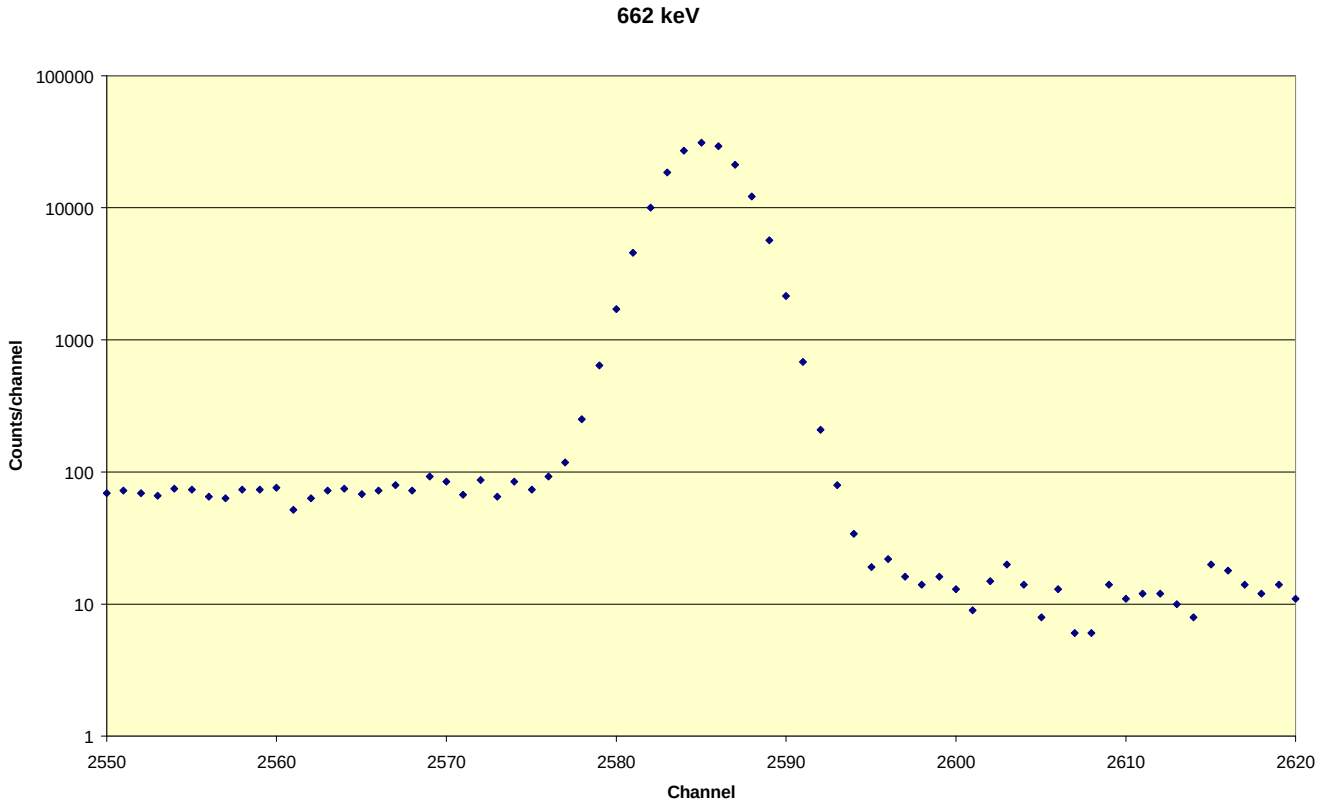
AUTOMATIC PEAK SEARCH

Result of automatic peak search



Expert visual checking recommended !

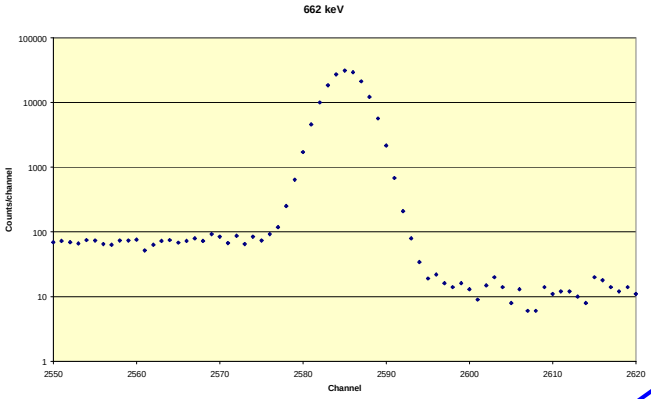
Processing of a single peak ROI

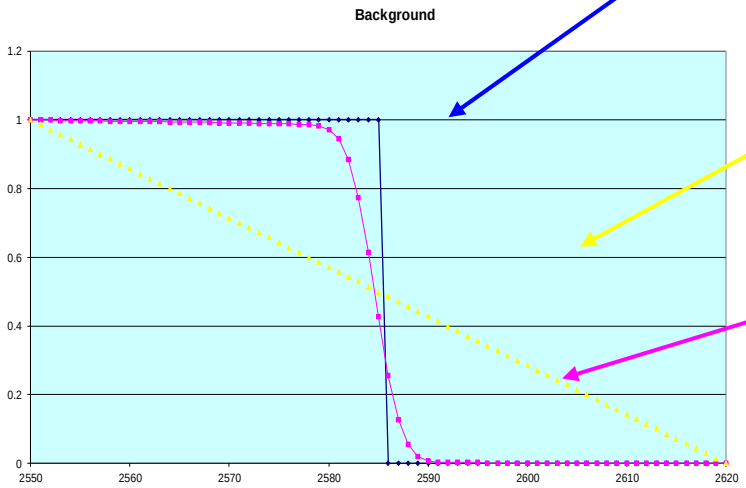


- Peak superimposed on a continuous background

Background

Peak with energy E_0 in region [f,l] first channel = f ; last channel = l





Step :

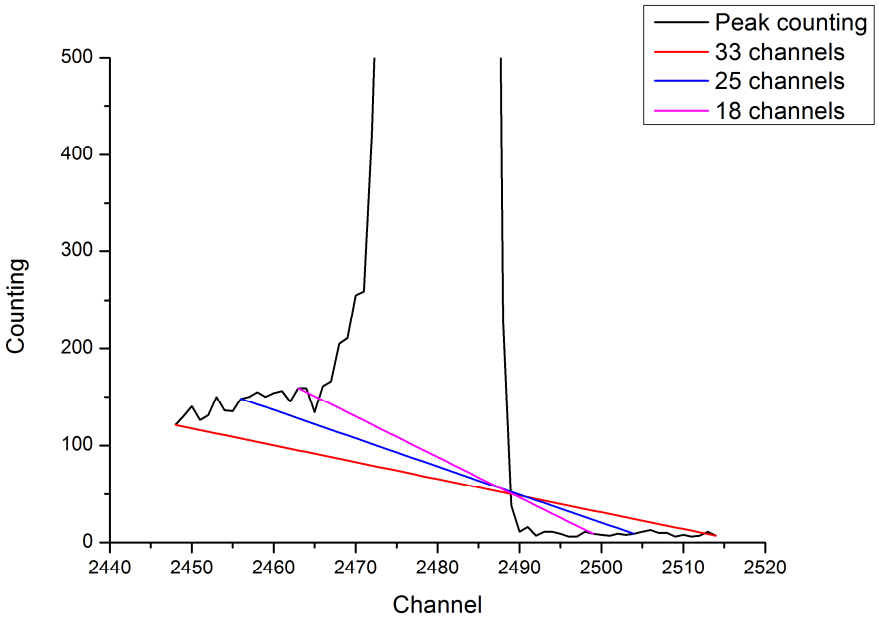
F(i) = 1 for E < E0

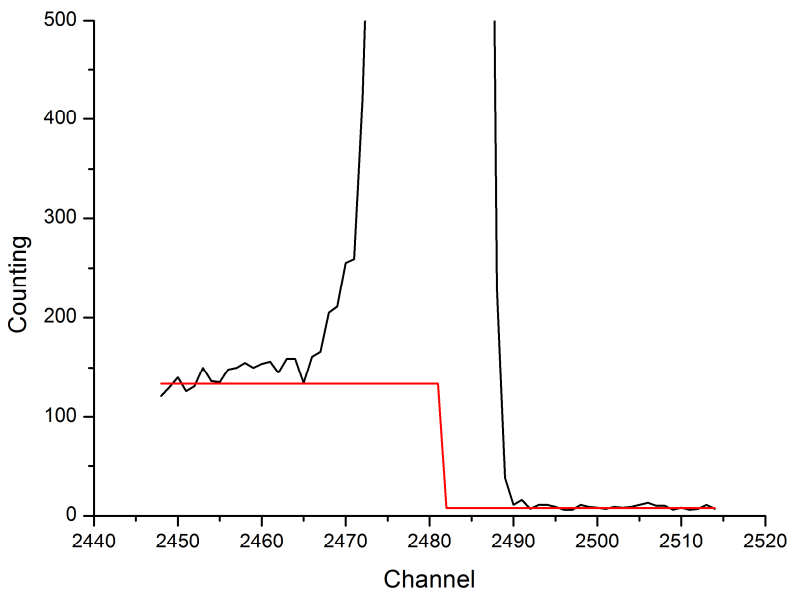
F(i) = 0 for E > E0

Linear : $F(i) = 1 - \frac{(i - f)}{(l - f)}$

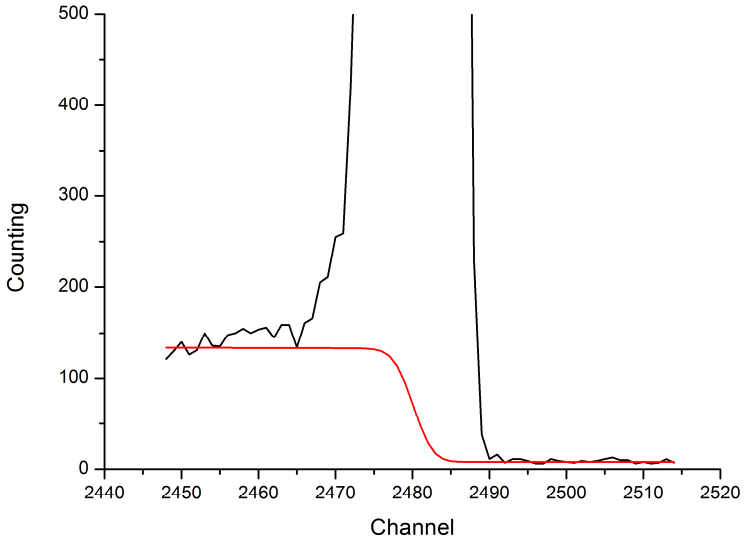
Galton curve : $F(i) = 1 - \frac{\sum_{f}^{i} Y_i}{\sum_{f}^{l} Y_i}$

Background





Background type	Gross area	Net area
Linear (33 channels)	943188	938907
Linear (25 channels)	942037	938191
Linear (18 channels)	940938	937830
Step (33 channels)	943188	938385
Galton (33 channels)	943188	938577



OUTLINE

General characteristics

Energy resolution

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Corrective factors

ATTENUATION (SCREEN)

Use of screen to reduce counting rate (X-rays, Bremsstrahlung)

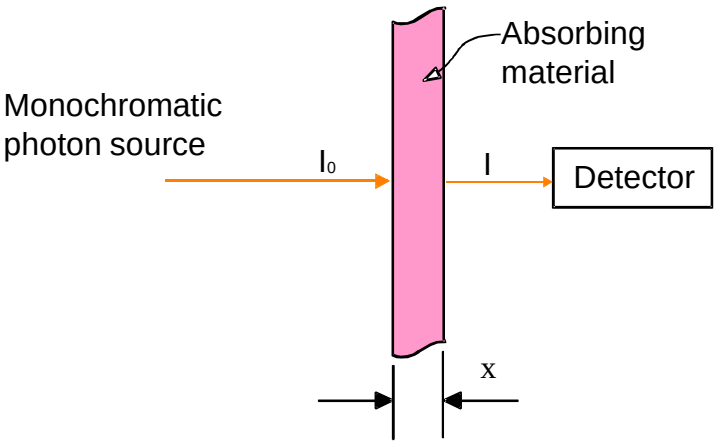
Beer-Lambert law

Mass attenuation coefficients

Beer-Lambert law

Attenuation of a narrow parallel photon beam

$$I(x) = I_0 \cdot e^{-\mu x} = I_0 \cdot e^{-\frac{\mu}{\rho}\rho x}$$



ρ = density (*g.cm*$^{-3}$)
μ = linear attenuation coefficient of material i for energy E (*cm*$^{-1}$)
ρ x = mass thickness (*g.cm*$^{-2}$)
μ / ρ = mass attenuation coefficient (*cm*^{2}*.g*$^{-1}$)

μ depends on E and Z

Attenuation coefficients

Practical parameter : Attenuation (absorption + scattering) coefficient

Partial interaction coefficients depend on the energy, E, and the material (Z):

Photoelectric absorption: $\tau_i(E)$ $\tau \approx \text{const}\, Z^{4.5} \cdot E^{-3}$ (dominant at low energies)

Compton scattering: $\sigma_i(E)$ $\sigma \approx \text{const} \cdot Z \cdot E^{-1}$

Pair production effect: $\kappa_i(E)$ $\kappa \approx \text{const} \cdot Z^2$ (only if E > 1022 keV)

For practical use : tables function of Z and E

Tables : cross sections (*1 barn = 10^{-24} cm^2*) or mass attenuation ($cm^2.g^{-1}$)

Interaction	Linear attenuation coefficient (cm^{-1})	Mass attenuation coefficient ($cm^2 \cdot g^{-1}$)
Photoelectric	τ	τ/ρ
Compton	σ	σ/ρ
Pair production	κ	κ/ρ
Total	$\mu=\tau+\sigma+\kappa$	$\mu/\rho=\tau/\rho+\sigma/\rho+\kappa/\rho$

Attenuation coefficients

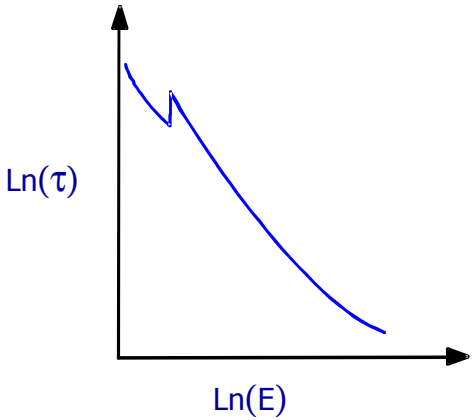
Photoelectric absorption coefficient = sum of photoelectric effect in each electronic shell (subshells):

$$\tau = \tau_K + (\tau_{L1} + \tau_{L2} + \tau_{L3}) + (\tau_{M1} + \tau_{M2} + \tau_{M3} + \tau_{M4} + \tau_{M5}) + \ldots$$

If E < binding energy of shell i, $\tau_i = 0$

For E = Ei : absorption discontinuity: maximum ionisation probability in shell i

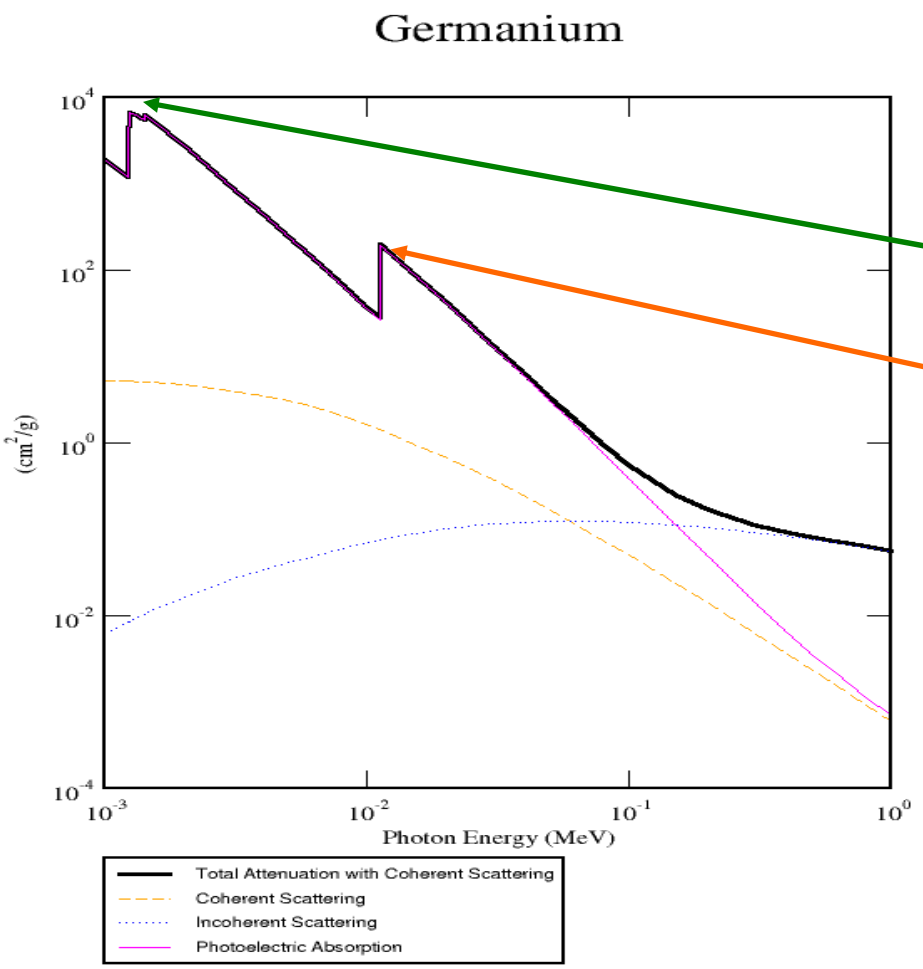
τ variation versus the energy shows discontinuities corresponding to binding energies of electrons shells and subshells K, L, M...



Since $\mu = \tau + \sigma + \kappa$
μ has the same discontinuities, function of the material atomic structure (Z)

Attenuation coefficients

Germanium mass attenuation coefficient



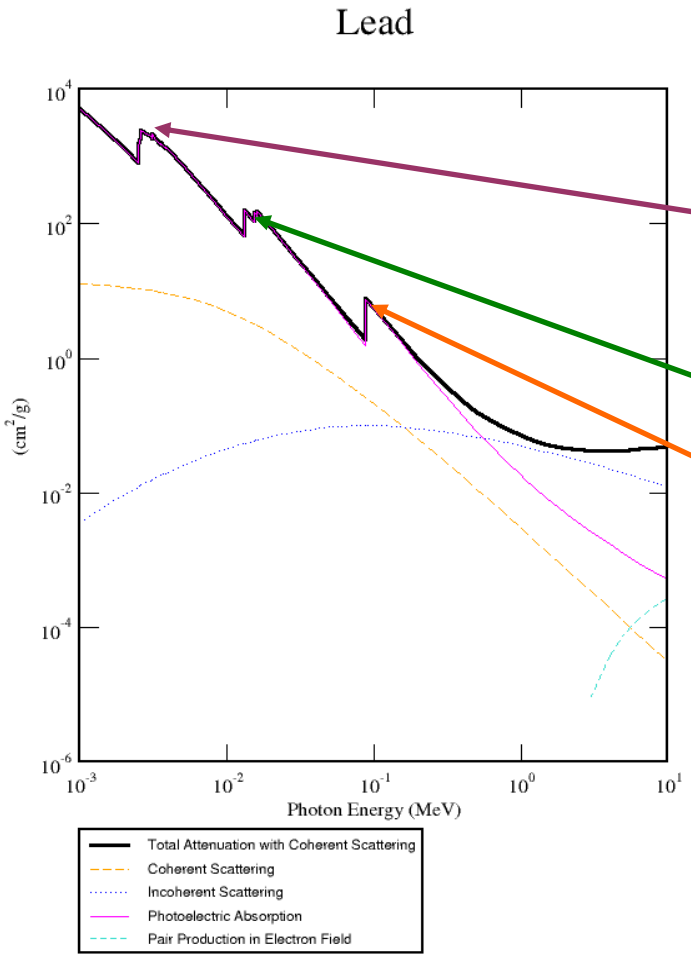
Ge binding energies :

L1: 1.4143
L2: 1.2478
L3: 1.2167

K: 11.1031

Attenuation coefficients

Lead mass attenuation coefficient



Pb binding energies :

M1: 3.8507
M2: 3.5542
M3: 3.0664
M4: 2.5856
M5: 2.4840

L1: 15.8608
L2: 15.2000
L3: 13.0352

K: 88.0045

Attenuation coefficients

Composition known -> calculation

Composition unknown -> measurement

Calculation: Attenuation coefficients table

- XCOM (NIST Database)
- Example for HCl 1N

Attenuation coefficients

Defining the mass fraction of each compound for HCl 1N:

Matrix : HCl 1N = 1 mole of HCl in 1 liter of solution

HCl 1N density = 1.016 (1L = 1016 g)

Mass of one HCl mole = 1+ 35.45 = 36.45 g

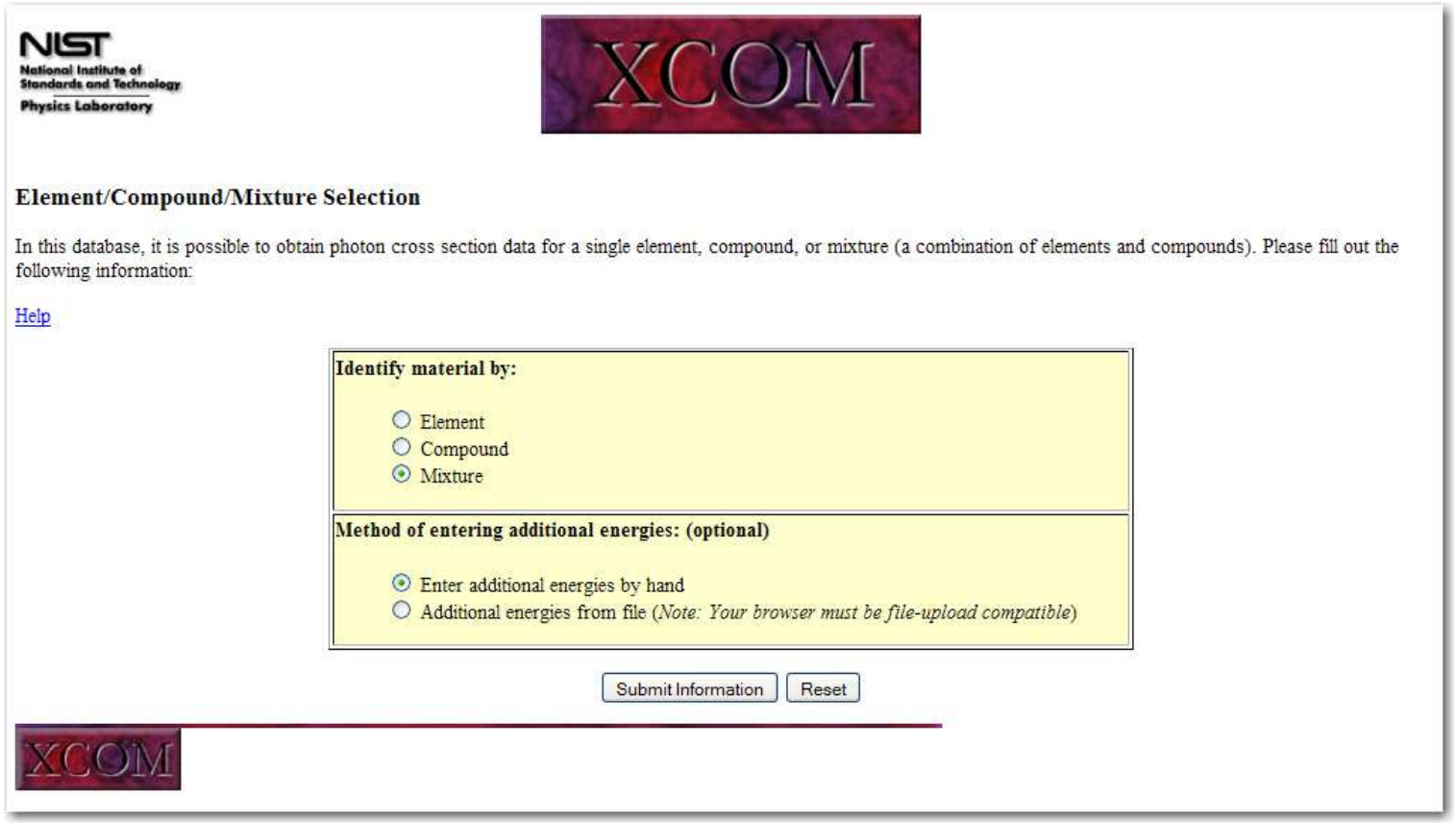
Resulting input parameters for XCOM

Compound 1: HCl
Mass fraction: 36.45

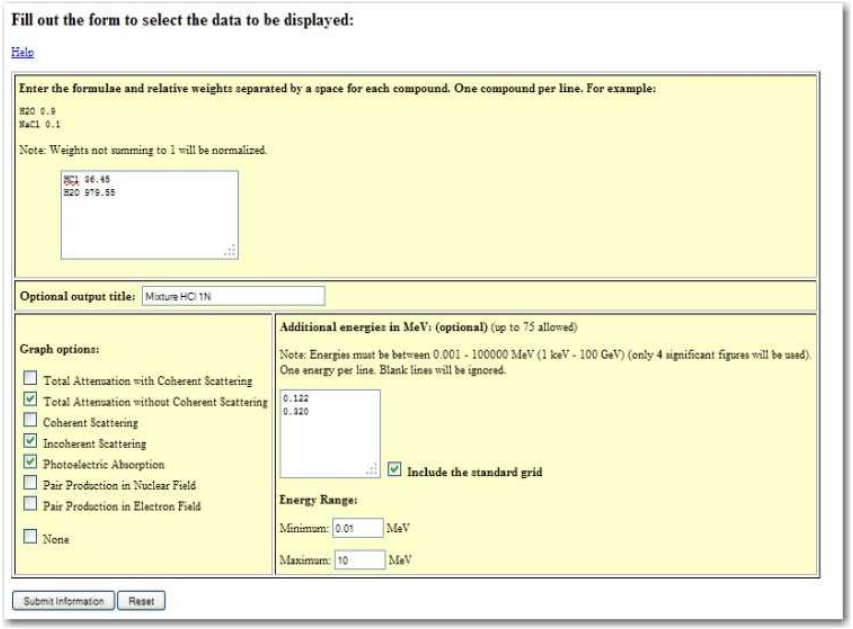
Compound 2: H_2O
Mass fraction = 1016 – 36.45 = 979.55

Attenuation coefficients

https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html



Attenuation coefficients



Fill out the form to select the data to be displayed:

Help

Enter the formulae and relative weights separated by a space for each compound. One compound per line. For example:

```
H2O 0.9
NaCl 0.1
```

Note: Weights not summing to 1 will be normalized.

```
HCl 36.45
H2O 979.55
```

Optional output title: Mixture HCl 1N

Graph options:

- ☐ Total Attenuation with Coherent Scattering
- ☑ Total Attenuation without Coherent Scattering
- ☐ Coherent Scattering
- ☑ Incoherent Scattering
- ☑ Photoelectric Absorption
- ☐ Pair Production in Nuclear Field
- ☐ Pair Production in Electron Field
- ☐ None

Additional energies in MeV: (optional) (up to 75 allowed)

Note: Energies must be between 0.001 - 100000 MeV (1 keV - 100 GeV) (only 4 significant figures will be used). One energy per line. Blank lines will be ignored.

```
0.122
0.320
```

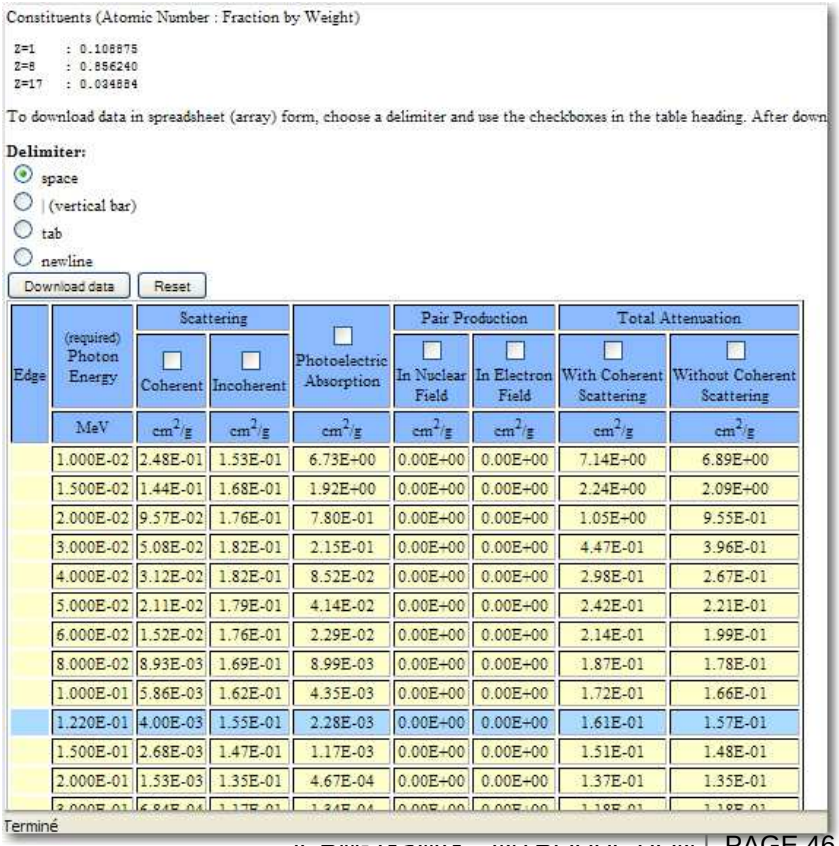
☑ **Include the standard grid**

Energy Range:

Minimum: 0.01 MeV

Maximum: 10 MeV

Submit Information | Reset



Constituents (Atomic Number : Fraction by Weight)

```
Z=1    : 0.108875
Z=8    : 0.856240
Z=17   : 0.034884
```

To download data in spreadsheet (array) form, choose a delimiter and use the checkboxes in the table heading. After down

Delimiter:

- ◉ space
- ○ | (vertical bar)
- ○ tab
- ○ newline

Download data | Reset

Edge	(required) Photon Energy	Scattering		☐ Photoelectric Absorption	Pair Production		Total Attenuation	
		☐ Coherent	☐ Incoherent		☐ In Nuclear Field	☐ In Electron Field	☐ With Coherent Scattering	☐ Without Coherent Scattering
	MeV	cm^2/g	cm^2/g	cm^2/g	cm^2/g	cm^2/g	cm^2/g	cm^2/g
	1.000E-02	2.48E-01	1.53E-01	6.73E+00	0.00E+00	0.00E+00	7.14E+00	6.89E+00
	1.500E-02	1.44E-01	1.68E-01	1.92E+00	0.00E+00	0.00E+00	2.24E+00	2.09E+00
	2.000E-02	9.57E-02	1.76E-01	7.80E-01	0.00E+00	0.00E+00	1.05E+00	9.55E-01
	3.000E-02	5.08E-02	1.82E-01	2.15E-01	0.00E+00	0.00E+00	4.47E-01	3.96E-01
	4.000E-02	3.12E-02	1.82E-01	8.52E-02	0.00E+00	0.00E+00	2.98E-01	2.67E-01
	5.000E-02	2.11E-02	1.79E-01	4.14E-02	0.00E+00	0.00E+00	2.42E-01	2.21E-01
	6.000E-02	1.52E-02	1.76E-01	2.29E-02	0.00E+00	0.00E+00	2.14E-01	1.99E-01
	8.000E-02	8.93E-03	1.69E-01	8.99E-03	0.00E+00	0.00E+00	1.87E-01	1.78E-01
	1.000E-01	5.86E-03	1.62E-01	4.35E-03	0.00E+00	0.00E+00	1.72E-01	1.66E-01
	1.220E-01	4.00E-03	1.55E-01	2.28E-03	0.00E+00	0.00E+00	1.61E-01	1.57E-01
	1.500E-01	2.68E-03	1.47E-01	1.17E-03	0.00E+00	0.00E+00	1.51E-01	1.48E-01
	2.000E-01	1.53E-03	1.35E-01	4.67E-04	0.00E+00	0.00E+00	1.37E-01	1.35E-01

Terminé

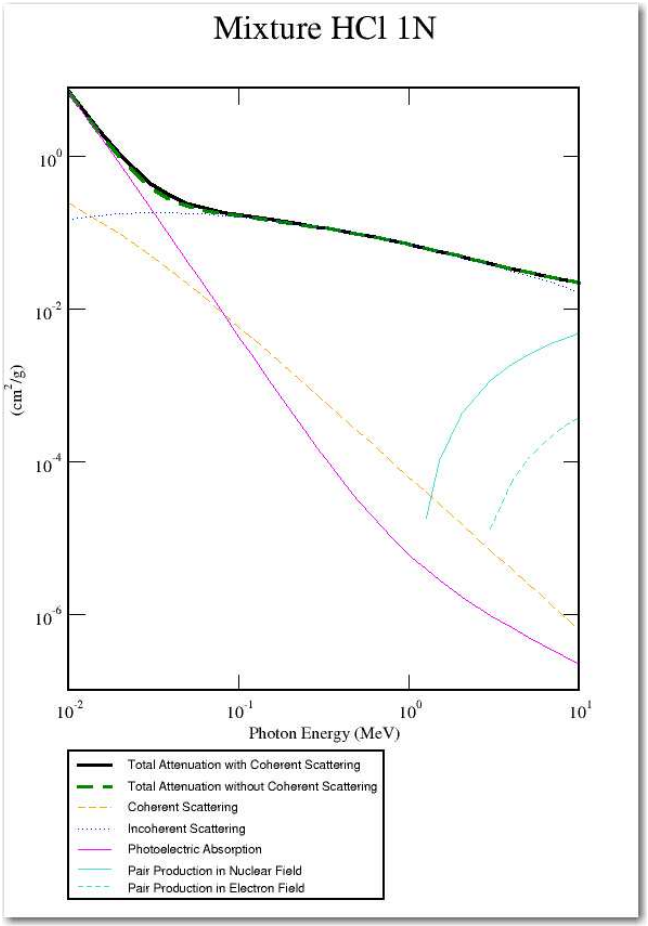
Attenuation coefficients

XCOM results

tab
newline
Download data | Reset

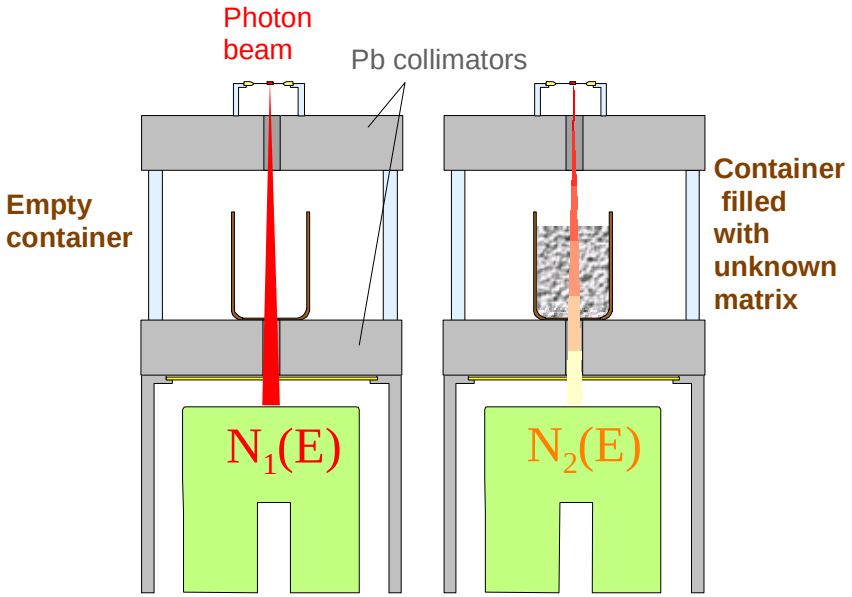
Edge	(required) Photon Energy	Scattering: Coherent	Scattering: Incoherent	Photoelectric Absorption	Pair Production: In Nuclear Field	Pair Production: In Electron Field	Total Attenuation: With Coherent Scattering	Total Attenuation: Without Coherent Scattering
	MeV	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g
	1.000E-03	1.43E+00	1.31E-02	4.03E+03	0.00E+00	0.00E+00	4.03E+03	4.03E+03
	1.500E-03	1.32E+00	2.65E-02	1.36E+03	0.00E+00	0.00E+00	1.36E+03	1.36E+03
	2.000E-03	1.20E+00	4.14E-02	6.10E+02	0.00E+00	0.00E+00	6.11E+02	6.10E+02
	2.822E-03	9.89E-01	6.52E-02	2.27E+02	0.00E+00	0.00E+00	2.28E+02	2.27E+02
17 K	2.822E-03	9.89E-01	6.52E-02	2.78E+02	0.00E+00	0.00E+00	2.79E+02	2.78E+02
	3.000E-03	9.47E-01	6.99E-02	2.36E+02	0.00E+00	0.00E+00	2.37E+02	2.36E+02
	4.000E-03	7.41E-01	9.32E-02	1.04E+02	0.00E+00	0.00E+00	1.04E+02	1.04E+02
	5.000E-03	5.86E-01	1.11E-01	5.40E+01	0.00E+00	0.00E+00	5.47E+01	5.41E+01
	6.000E-03	4.75E-01	1.24E-01	3.15E+01	0.00E+00	0.00E+00	3.21E+01	3.16E+01
	8.000E-03	3.31E-01	1.42E-01	1.33E+01	0.00E+00	0.00E+00	1.38E+01	1.34E+01
	1.000E-02	2.48E-01	1.53E-01	6.73E+00	0.00E+00	0.00E+00	7.14E+00	6.89E+00
	1.500E-02	1.44E-01	1.68E-01	1.92E+00	0.00E+00	0.00E+00	2.24E+00	2.09E+00
	2.000E-02	9.57E-02	1.76E-01	7.80E-01	0.00E+00	0.00E+00	1.05E+00	9.55E-01
	3.000E-02	5.08E-02	1.82E-01	2.15E-01	0.00E+00	0.00E+00	4.47E-01	3.96E-01
	4.000E-02	3.12E-02	1.82E-01	8.52E-02	0.00E+00	0.00E+00	2.98E-01	2.67E-01
	5.000E-02	2.11E-02	1.79E-01	4.14E-02	0.00E+00	0.00E+00	2.42E-01	2.21E-01
	6.000E-02	1.52E-02	1.76E-01	2.29E-02	0.00E+00	0.00E+00	2.14E-01	1.99E-01
	8.000E-02	8.93E-03	1.69E-01	8.99E-03	0.00E+00	0.00E+00	1.87E-01	1.78E-01
	1.000E-01	5.86E-03	1.62E-01	4.35E-03	0.00E+00	0.00E+00	1.72E-01	1.66E-01
	1.500E-01	2.68E-03	1.47E-01	1.17E-03	0.00E+00	0.00E+00	1.51E-01	1.48E-01
	2.000E-01	1.53E-03	1.35E-01	4.67E-04	0.00E+00	0.00E+00	1.37E-01	1.35E-01
	3.000E-01	6.84E-04	1.17E-01	1.34E-04	0.00E+00	0.00E+00	1.18E-01	1.18E-01
	4.000E-01	3.86E-04	1.05E-01	5.76E-05	0.00E+00	0.00E+00	1.06E-01	1.05E-01
	5.000E-01	2.48E-04	9.62E-02	3.12E-05	0.00E+00	0.00E+00	9.65E-02	9.63E-02
	5.140E-01	2.34E-04	9.51E-02	2.90E-05	0.00E+00	0.00E+00	9.54E-02	9.52E-02
	6.000E-01	1.72E-04	8.90E-02	1.95E-05	0.00E+00	0.00E+00	8.92E-02	8.91E-02
	8.000E-01	9.69E-05	7.82E-02	9.83E-06	0.00E+00	0.00E+00	7.84E-02	7.83E-02
	1.000E+00	6.20E-05	7.04E-02	6.11E-06	0.00E+00	0.00E+00	7.04E-02	7.04E-02
	1.022E+00	5.94E-05	6.96E-02	5.73E-06	0.00E+00	0.00E+00	6.97E-02	6.96E-02
	1.173E+00	4.51E-05	6.50E-02	4.30E-06	6.51E-06	0.00E+00	6.51E-02	6.50E-02
	1.250E+00	3.97E-05	6.29E-02	3.89E-06	1.86E-05	0.00E+00	6.30E-02	6.29E-02
	1.331E+00	3.50E-05	6.09E-02	3.50E-06	3.87E-05	0.00E+00	6.10E-02	6.10E-02

Terminé | Internet | 75%



EXPERIMENTAL MEASUREMENT

Principle : Use the unknown matrix and a collimated photon beam



Two successive measurements

- Empty container
- Container filled with unknown matrix with thickness x

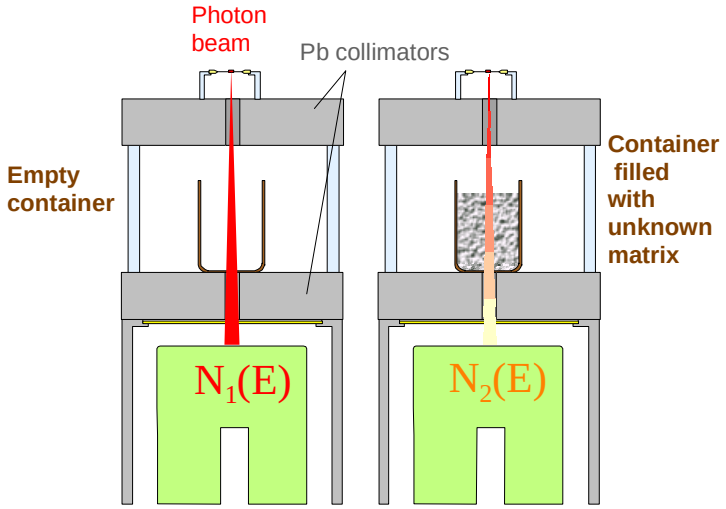
Experimental measurement

For each energy:

$$N_2(E) = N_1(E) \,.\, exp\,(-\mu(E) \,.\, x)$$

Thus:

$$\mu(E) = \frac{1}{x}\, ln\left(\frac{N_2(E)}{N_1(E)}\right)$$

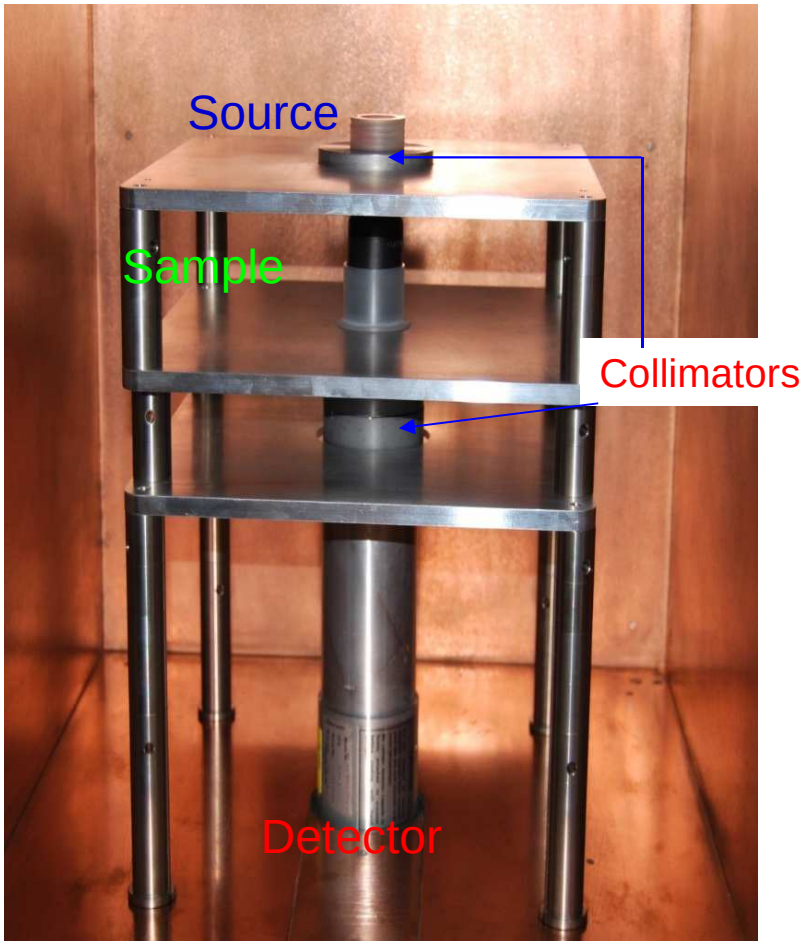


Associated relative uncertainty:

$$\frac{u^2(\mu)}{\mu^2} = \frac{u^2(x)}{x^2} + \frac{1}{\ln^2\left(\frac{N_0(E)}{N(E)}\right)} \cdot \left(\frac{u^2(N_0(E))}{N_0^2(E)} + \frac{u^2(N(E))}{N^2(E)}\right)$$

Experimental measurement

Dedicated experimental arrangement :



Example of steel sample

^{60}Co in steel sample

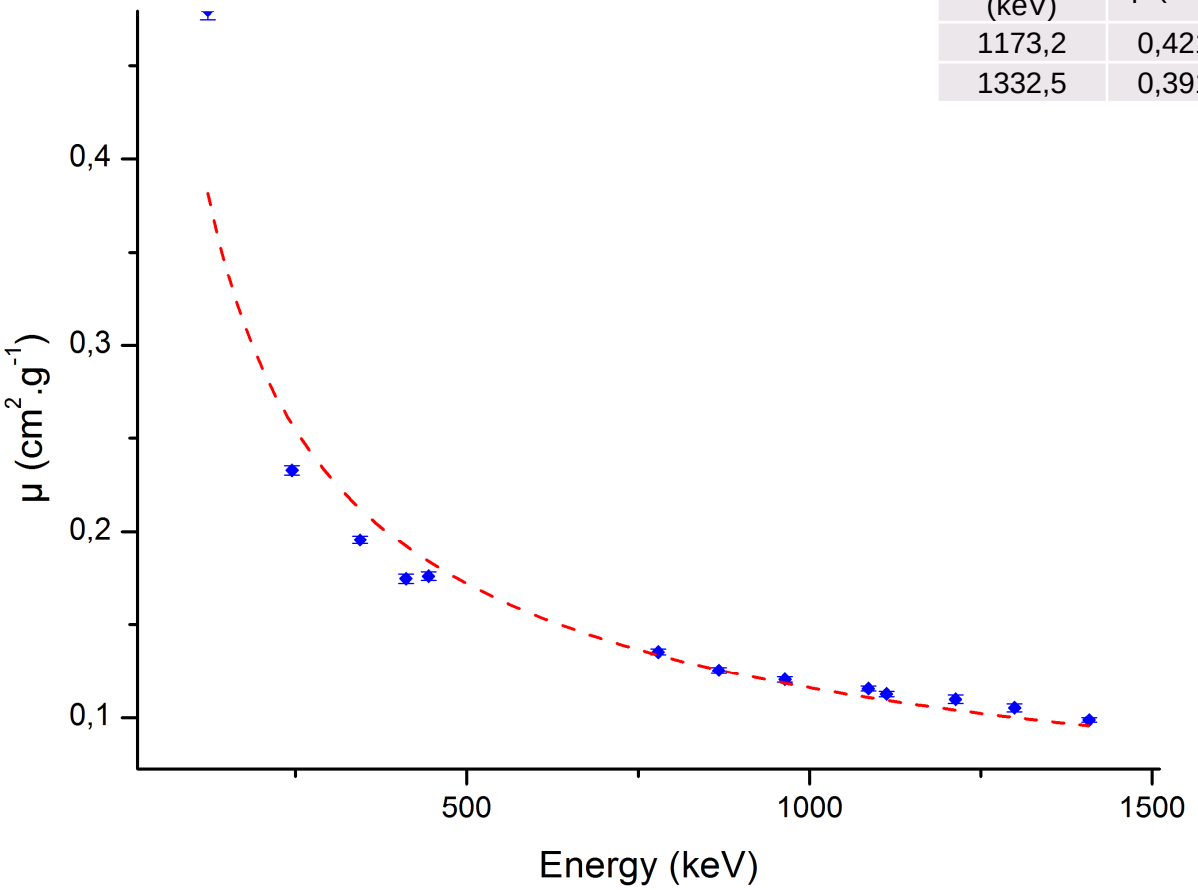
		Eu-152	13,522	0,016						
			4,2671E+08	5,0E+05			1 a =	j		
			7,1119E+06	8,4E+03			1 a =	s		
			1,1853E+05	1,4E+02						
			4,9388E+03	5,8E+00		Date et heure de référence		25/03/2018 12:00		
			1,3522E+01	1,6E-02						
	Eu-152 without material		**Eu-152 with mterial**		**Attenuation results**					
					Material mass (m)		75,8032	g		
	Start	26/03/2018	Start	27/03/2018		Stand. unc.	0,0008	g		
	Real time	80226,6	Real time	77741,46	Diameter (D)		3,5	cm		
	Active time	77393,3	Active time	74906,12		Stand. unc.	0,02	cm		
	% TM	3,5%	% TM	3,6%	Height (x)		1	cm		
	Half-life cor	1,0001E+00	Half-life cor	1,0003E+00		Stand. unc.	0,01	cm		
	Decay corr.	1,0001E+00	Decay corr.	1,0001E+00	Density (ρ)		3,94	g.cm^{-3}		
						Stand. unc.	0,01	g.cm^{-3}		
Energy (keV)	**NET**	**Rel. Stand. Unc**	**NET**	**el. Stand. Un**	**I/I0**	**el. Stand. Un**	**μ (cm^{-1})**	**el. Stand. Un**	**μ (cm².g^{-1})**	**Rel. Stand. Unc**
121,78	2248977	0,1%	328827	0,2%	0,1511	0,2%	1,890	1,0%	0,480	1,0%
244,70	412482	0,2%	159477	0,3%	0,3995	0,3%	0,917	1,1%	0,233	1,1%
344,28	1096300	0,1%	491001	0,1%	0,4628	0,2%	0,770	1,0%	0,196	1,1%
411,12	66423	0,4%	32317	0,6%	0,5028	0,7%	0,688	1,4%	0,175	1,4%
443,97	108192	0,3%	52366	0,4%	0,5001	0,5%	0,693	1,3%	0,176	1,3%
778,90	399743	0,2%	226912	0,2%	0,5866	0,3%	0,533	1,1%	0,135	1,2%
867,38	131623	0,3%	77692	0,4%	0,6099	0,5%	0,494	1,4%	0,125	1,4%
964,08	454460	0,1%	273614	0,2%	0,6221	0,2%	0,475	1,1%	0,120	1,2%
1085,84	371627	0,2%	228130	0,2%	0,6343	0,3%	0,455	1,2%	0,116	1,2%
1112,08	428505	0,2%	266091	0,2%	0,6417	0,2%	0,444	1,1%	0,113	1,2%
1212,95	43790	0,5%	27500	0,6%	0,6489	0,8%	0,432	2,0%	0,110	2,1%
1299,14	53310	0,4%	34077	0,5%	0,6605	0,7%	0,415	1,9%	0,105	2,0%
1408,01	638601	0,1%	418820	0,2%	0,6777	0,2%	0,389	1,1%	0,099	1,2%

$$\mu(cm^{-1}) = \frac{-\ln\left(\frac{I}{I_0}\right)}{x}$$

$$\mu(cm^{1}.g^{-1}) = \frac{\mu(cm^{-1})}{\rho}$$

Example of steel sample

Energy (keV)	μ (cm^{-1})	μ ($cm^2.g^{-1}$)
1173,2	0,4212	0,1069
1332,5	0,3917	0,0994



OUTLINE

General characteristics

Energy resolution

Peak area

Attenuation

Corrective factors

CORRECTIVE FACTORS

Half-life correction

Decay correction (short half-lifes)

Attenuation correction (screen)

Self-attenuation correction (see “Self attenuation” section)

Geometry correction (source-detector distance)

Coincidence summing correction (see “Coincidence summing ” section)

Background peaks

Escape peaks (annihilation or characteristics Ge X-rays)

Dead time correction

In-flight annihilation correction (Beta plus emitters)

HALF-LIFE

Measurement at a date different from the reference time
To get the counting rate at the reference time: C_T

$T_{1/2}$: radionuclide half-life

T_0 : reference time

T_m : acquisition start time

$$C_T = \exp\left(\ln(2) \cdot \frac{(T_m - T_0)}{T_{1/2}}\right)$$

DECAY DURING MEASUREMENT

The radionuclide decays during the measurement

If T_r not negligible versus $T_{1/2}$:

$$C_D = \frac{\ln(2) \cdot \left(T_r / T_{1/2}\right)}{1 - \exp\left(-\ln(2) \cdot \left(T_r / T_{1/2}\right)\right)}$$

Or: $C_D = \frac{\lambda \cdot T_r}{1 - \exp(-\lambda \cdot T_r)}$ where $\lambda = \frac{\ln(2)}{T_{1/2}}$

$T_{1/2}$: radionuclide half-life

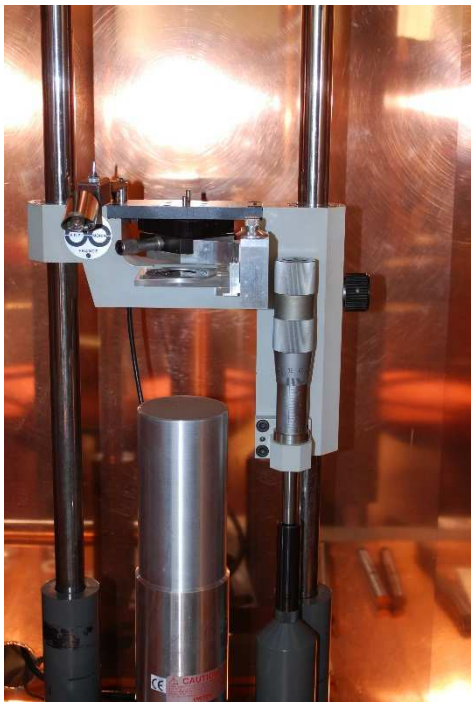
T_r : acquisition time (clock - real time !)

T_m : acquisition start time

GEOMETRY CORRECTION

Efficiency calibration

- Characteristic of the detector.
- Defined for an incident energy and source-detector geometry



Sample with different geometry to be measured

- - self-absorption
- - geometry variation (solid angle)

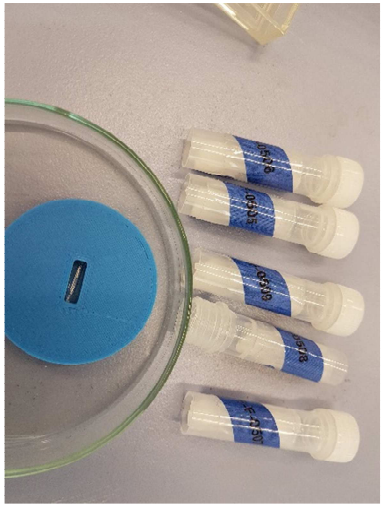
Calibration sources

Calibration sources

Large number of geometries and matrices :

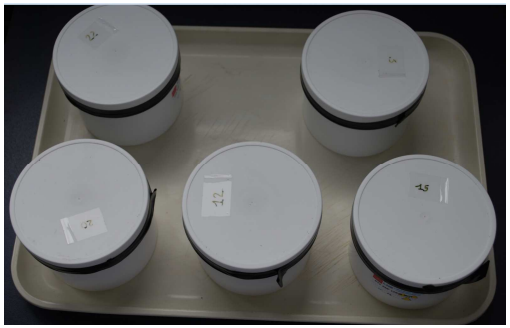
- point source

- disk-shape samples (filters)



- cylindrical geometries
  - liquid
  - solid
  - gas

- Marinelli geometries (Environment)
  - liquid
  - solid
  - gas



SOURCE-TO-DETECTOR GEOMETRY

Source-to-detector distance can be adapted according to the counting rate

Small distance : Higher count rate

- -> Smaller counting time
- -> Less influence of the environmental background
- -> Possiblitlity to use smaller samples (less self-absorption)

Large distance : Lower count rate

- -> Less pile-up
- -> Reduction of the coincidence summing effect
- -> Accuracy of the position (relative uncertainty)

Compromise between counting time and corrective factors

Efficiency transfer principle (Moens)

Calibration geometry :

Full-energy peak efficiency : $\varepsilon_0(E) = \varepsilon_0^G \cdot \varepsilon^I(E)$

Where $\varepsilon_0^G = \frac{\Omega_0}{4\pi}$

Measurement geometry :

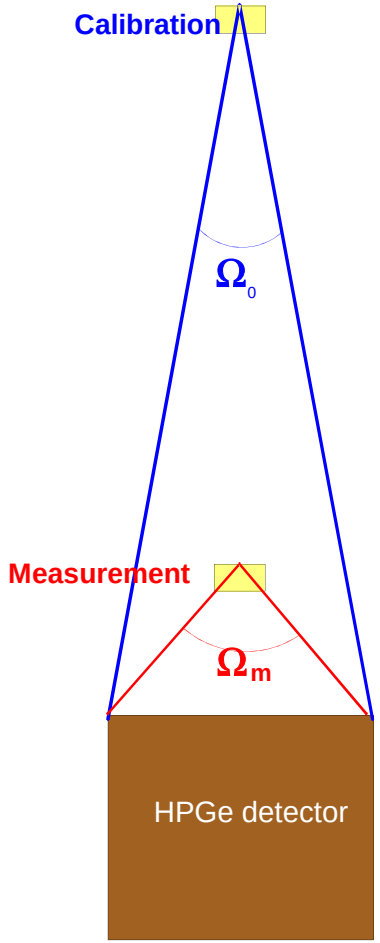
Full-energy peak efficiency : $\varepsilon_m(E) = \varepsilon_m^G \cdot \varepsilon^I(E)$

Where $\varepsilon_m^G = \frac{\Omega_m}{4\pi}$

$$\varepsilon_m(E) = \varepsilon_0(E) \cdot \frac{\Omega_m}{\Omega_0}$$

Only valid for point sources

Volume: self-attenuation (+ matrix + source dimensions)



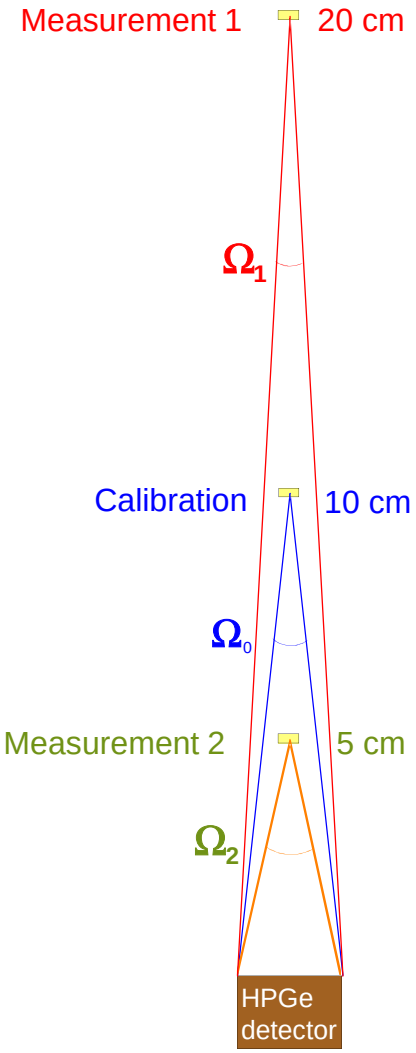
Efficiency transfer example

Efficiency calibration at 100 keV = 0.0171

Detector radius : r= 2 cm

Source - detector distance for calibration : d_0= 10 cm

$$\Omega_0 = 2\pi\left(1 - \frac{d_0}{\sqrt{{d_0}^2 + r^2}}\right) = 0.122$$



Source - detector distance for measurement (m1) : dm1=20 cm

Ω_{m1} = 0.031 sr Ω_{m1}/Ω_0 = 0.25

Source - detector distance for measurement (m2) : dm2= 5 cm

Ω_{m2} = 0.449 sr Ω_{m2}/Ω_0 = 3.7

Efficiency transfer example

at 20 cm :

$$\varepsilon_{m1}(100) = \varepsilon_0\,(100) \cdot \frac{\Omega_{m1}}{\Omega_0} = 0.0171 \cdot \frac{0.031}{0.122} = 0.0043$$

at 5 cm :

$$\varepsilon_{m2}(100) = \varepsilon_0\,(100) \cdot \frac{\Omega_{m2}}{\Omega_0} = 0.0171 \cdot \frac{0.449}{0.122} = 0.0629$$

Approximation $$\Omega_0 = 2\pi\left(1 - \frac{d_0}{\sqrt{{d_0}^2 + r^2}}\right) \approx 2\pi\left(1 - \left(1 - \frac{r^2}{2d^2}\right)\right) = \pi \cdot \frac{r^2}{d^2}$$

$$\frac{\Omega_m}{\Omega_0} = \frac{d_0^2}{d_m^2}$$

$$\varepsilon_{m1}(100) = \varepsilon_0\,(100) \cdot \frac{d_0^2}{d_{m1}^2} = 0.0171 \cdot \frac{(10)^2}{(20)^2} = 0.0043 \qquad \Delta = \text{negligible}$$

$$\varepsilon_{m2}(100) = \varepsilon_0\,(100) \cdot \frac{d_0^2}{d_{m2}^2} = 0.0171 \cdot \frac{(10)^2}{(5)^2} = 0.0684 \qquad \Delta = +\,9\%$$

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THANK YOU FOR YOUR ATTENTION !