Detector efficiency calibration basics

NKS GammaSkill 2023, 26/09/2023, STUK

Guillaume Lutter

References

- *Practical Gamma-ray Spectrometry – 2nd edition*, G. Gilmore, John Wiley & Son Ltd, 2008.
- *Full Energy Peak efficiency*, G. Lutter, Basics of gamma-ray spectrometry and analysis of food and feed, EC-JRC-Geel, 30/01/2018.
- *Genie 2000 – Customization Tools Manual v3.4*, Canberra, 2013.
- *Detection efficiency*, M-C Lépy, LNHB, IAEA-ALMERA Technical Visit, 07/2010.
- *Basic hands-on gamma calibration for low activity environmental levels*, I. Osvath, IAEA, Nucleonica wiki, 2016.

www.nucleonica.com/wiki/images/1/16/NuTRoNS2_HandsonGamma.pdf

- *Experimental Efficiency calibration*, M. Bruggeman, SCK·CEN Academy, EC-JRC Enlargement & Integration Action, Vinča Institute of Nuclear Sciences, Belgrade, 11/2014.
- *Efficiency Transfer*, T. Vidmar, SCK·CEN Academy, EC-JRC Enlargement & Integration Action, Vinča Institute of Nuclear Sciences, Belgrade, 11/2014.

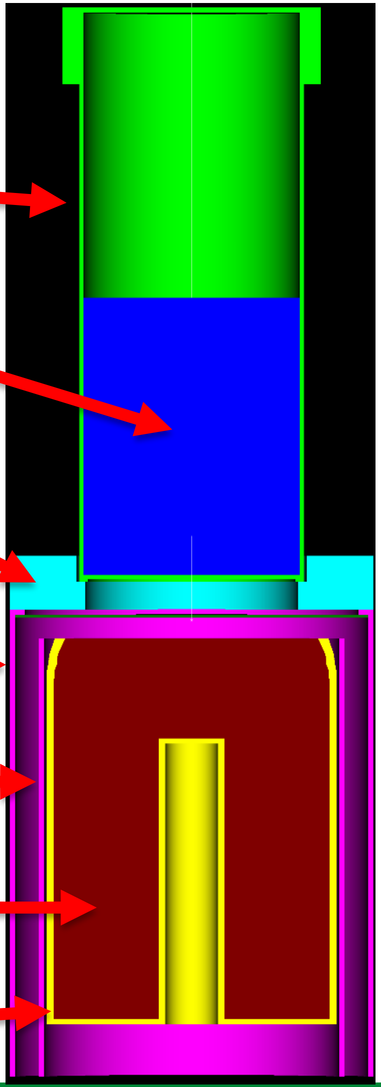
Definition

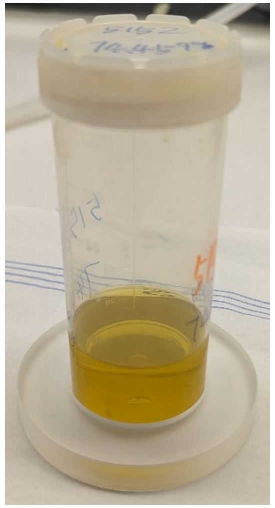
Sample:

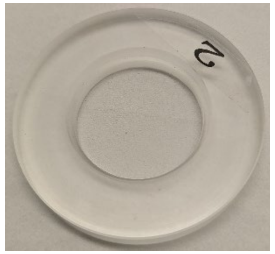
- Container
- Active sample
- Sample holder

HPGe detector:

- Endcap
- Crystal holder
- Crystal (Ge)
- Dead layer







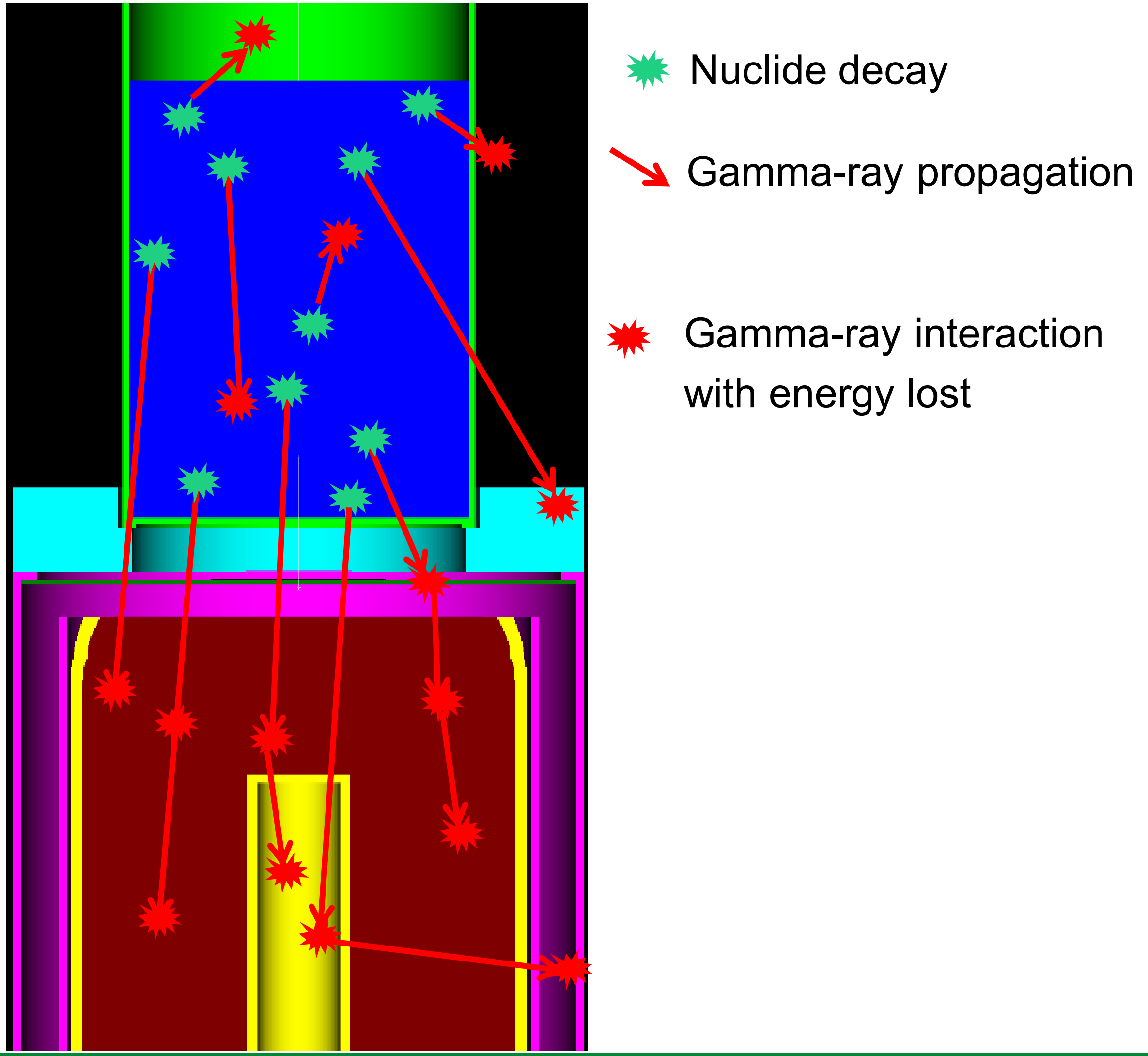
Definition

Sample:

- Active sample

HPGe detector:

- Crystal (Ge)



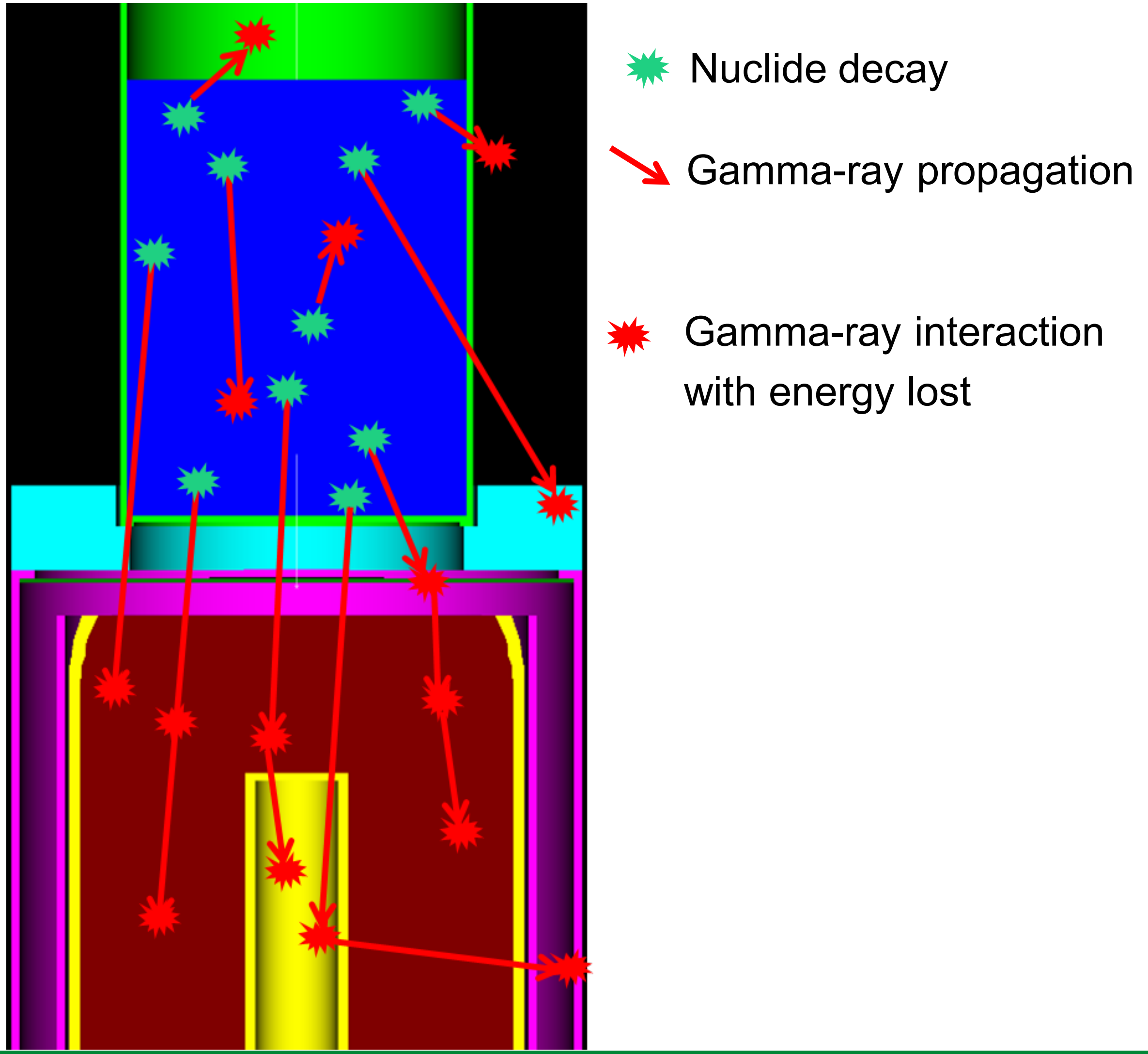
Definition

$$Efficiency = \frac{\text{Number of gamma} - \text{rays which } \color{red}{\text{interacts}} \text{ in the } \color{red}{\text{germanium}}^{*}}{\text{Number of gamma} - \text{rays emitted by the source}}$$

= 4

= 10

$$= Total\ Efficiency$$



* Assuming all the energy deposited is collected

Definition: Full Energy Peak Efficiency

For a given gamma-ray energy:

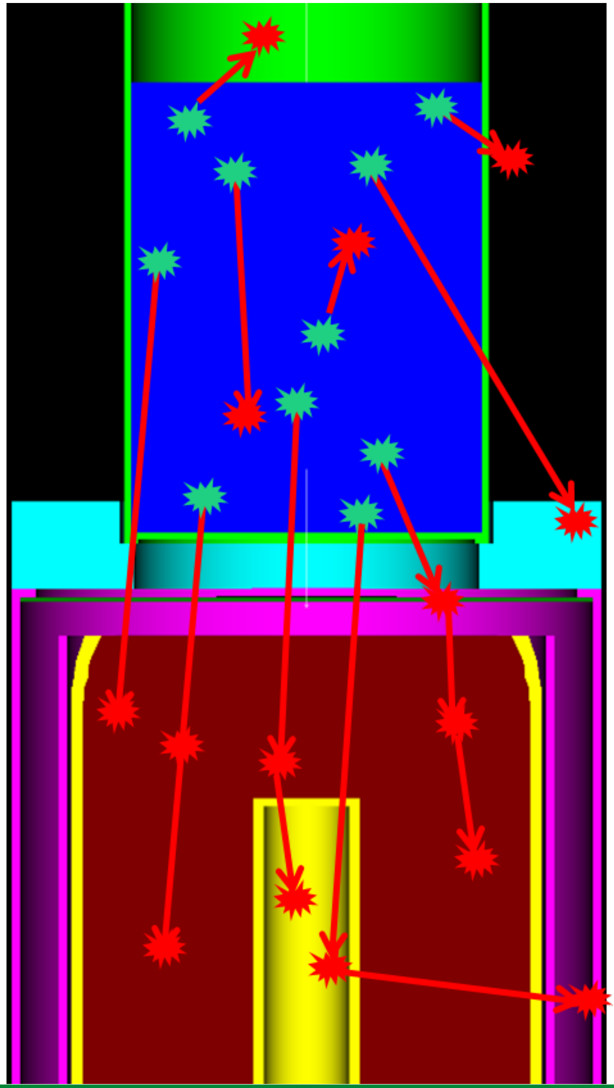
and deposits all their energy

$$Efficiency = \frac{\text{Number of gamma} - \text{rays which interacts in the germanium}^{*}}{\text{Number of gamma} - \text{rays emitted by the source}}$$

= 2

= 10

$$= FEP\ Efficiency$$



Nuclide decay

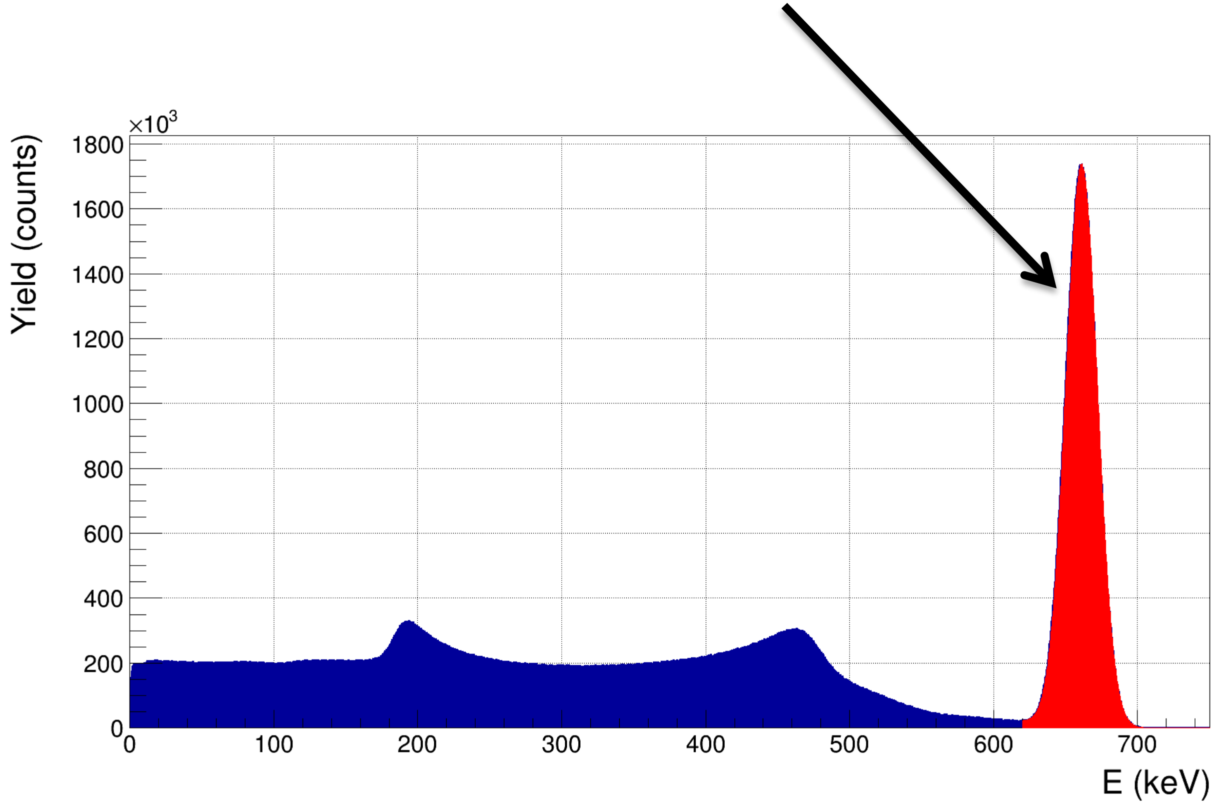
Gamma-ray propagation

Gamma-ray interaction with energy lost

* Assuming all the energy deposited is collected

Definition: Full Energy Peak Efficiency (Ɛ)

"ratio of the number of counts detected in a peak to the number emitted by the source"



(Total efficiency: ratio of the total number of counts [blue+red] detected to the number emitted by the source)

Definition: Full Energy Peak Efficiency (Ɛ)

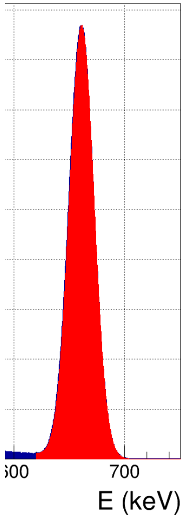
At a given energy, to be in the peak, each gamma-ray needs to:

- ✓ Escape the sample,
- ✓ Be in the solid angle of the detector,
- ✓ Cross all materials (air, sample holder, endcap/window,…),
- ✓ Pass the germanium dead-layer

without energy lost

and

- ✓ Be entirely absorbed in the active part of the germanium crystal
- ✓ Be completely '*collected*' by electronics



FEP efficiency depends:

- ➢ Energy of the particle,
- ➢ Sample composition (also container),
- ➢ Sample density,
- ➢ Sample geometry,
- ➢ Distance sample-detector,
- ➢ Type of detector (+ electronics)

How To

Get the FEP Efficiencies

- Theoretical way
- Experimental way
- Computer simulations (Monte Carlo)

Theoretical way

For a given energy E:

$$\varepsilon(E) \approx \int_{\Omega} \prod_i \left(e^{-\mu_i(E).x_i}\right) \times \left(1 - e^{-\mu_d(E).x_d}\right) \times P_{tot}(E) \times d\Omega$$

Transmission through materials

Interaction in the active germanium crystal

Probability of total absorption in the active Ge crystal

Solid angle between the source and the detector

(source: *Detection efficiency*, M-C Lépy, LNE-LNHB)

Experimental way

Activity calculation formula:

$$A = \frac{C}{P_\gamma \times t_l \times \boldsymbol{\varepsilon}} \times e^{\lambda . t_d} \times \frac{\lambda . t_r}{1 - e^{-\lambda . t_r}}$$

A	Activity, in Bq
C	Counts in the full energy peak at energy E, continuum and background subtracted
P_γ	absolute emission probability per decay of the gamma-ray
t_l	live counting time, in s
ε	**full energy peak efficiency at energy E for a given setup and radionuclide**
λ	decay constant, in s^{-1}
t_d	time elapsed from the reference date to the start of the measurement, in s
t_r	real counting time, in s

Experimental way

FEP efficiency calculation formula:

Data acquisition

Decay data

Manufacturer, sampling date, customers,…

$$\varepsilon = \frac{C}{A \times P_\gamma \times t_l} \times e^{\lambda . t_d} \times \frac{\lambda . t_r}{1 - e^{-\lambda . t_r}}$$

??

A	Activity, in Bq
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Experimental way

FEP efficiency calculation formula:

Data acquisition

Decay data

Manufacturer, sampling date, customers,…

Calibration standard

$$\varepsilon = \frac{C}{A \times P_\gamma \times t_l} \times e^{\lambda . t_d} \times \frac{\lambda . t_r}{1 - e^{-\lambda . t_r}}$$

A	Activity, in Bq
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ε	**full energy peak efficiency at energy E for a given setup and radionuclide**
λ	decay constant, in s^{-1}
t_d	time elapsed from the reference date to the start of the measurement, in s
t_r	real counting time, in s

Prerequirements

- Good & up to date decay data: Half-Lives, Emission probabilities

  Decay Data Evaluation Group:

  www.lnhb.fr/nuclear-data/nuclear-data-table **(not all nuclides are available)**

  If not available on previous link

  www.nndc.bnl.gov

- Good energy calibration: Peak identification (energy, area)

- Stable electronics with appropriate settings (pile-up, dead time,…)

Experimental data

- Use only peaks with sufficient counting statistics (>10 000 counts)
- Use peaks with well-defined shape
- Use peaks which have no interference and no background (or negligible)
- Correct for decay
- Correct for coincidence summing effect

Experimental way:

Calibration standard

Calibration standard

- Definition:

'*Something*' which has
- ✓ Same composition
- ✓ Same density
- ✓ Same geometry
- ✓ Same radionuclide(s)

as your sample

- Procedure:

1. Place the calibration standard at the same position as your sample
2. Measure it to get enough statistics in the peak(s)
3. Analyse the acquired spectrum in the same way as your sample (peak area, background subtraction,…)
4. Use formula slide 12 to get the FEP efficiency(ies)
5. **Done !**

→ You can use the FEP efficiency(ies) to calculate the sample activity(ies)

Calibration standard

- Definition:

  '*Something*' which has
  - ✓ Same composition as your sample
  - ✓ Same density
  - ✓ Same geometry
  - ✓ **Different radionuclide(s)**

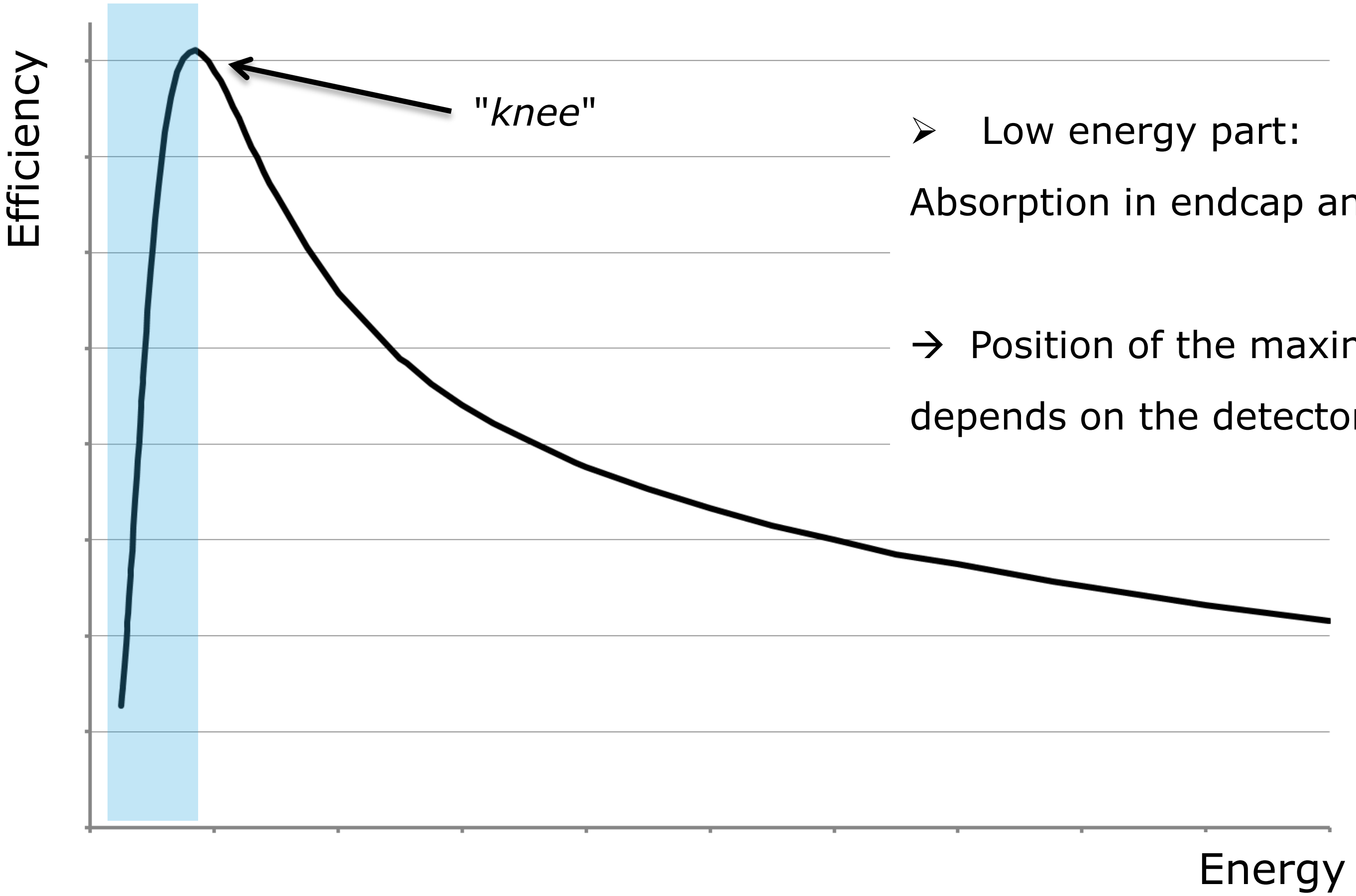
- Procedure:

  1. Place the calibration standard at the same position as your sample
  2. Measure it to get enough statistics in the peak(s)
  3. Analyse the acquired spectrum in the same way as your sample (peak area, background subtraction,…)
  4. Use formula slide 12 to get the FEP efficiency(ies)
  5. Experimental FEP efficiency(ies) ≠ needed FEP efficiency(ies)

  → FEP efficiency curve

FEP efficiency curve

Typical shape:



- Low energy part:

Absorption in endcap and dead-layer(s)

→ Position of the maximum efficiency (~80-130 keV) depends on the detector

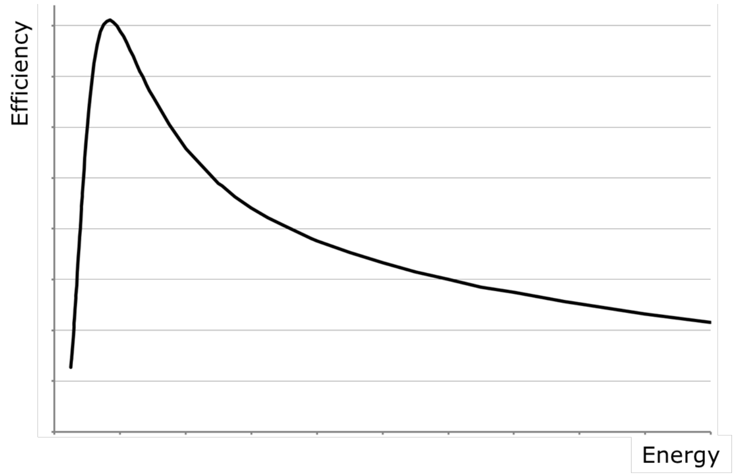
- Get the FEP efficiency at any energy

FEP efficiency curve: How To

✓ Check the energy range of interest

→ Need calibration standard(s) with:

gamma-ray emitter(s) within this range



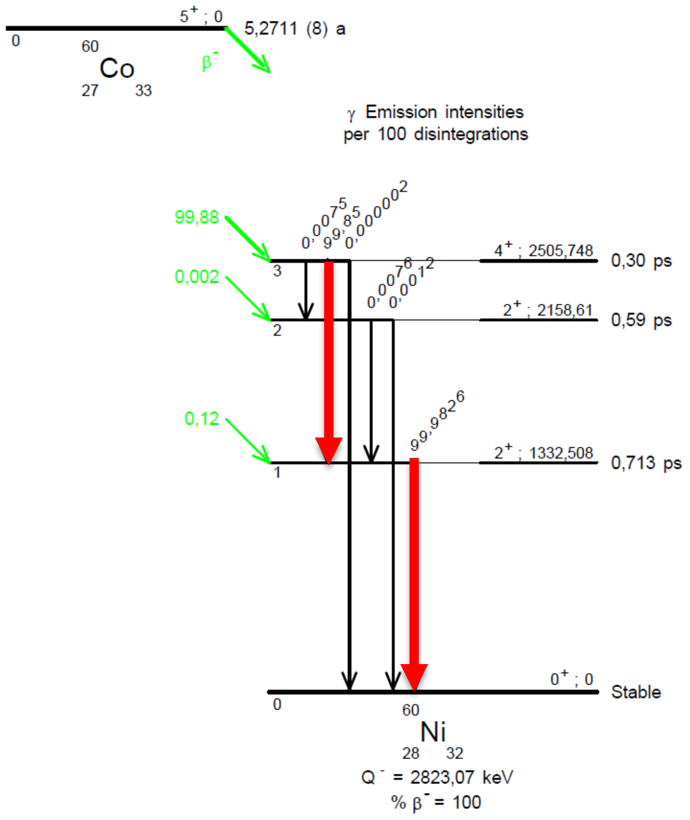
Several single gamma-ray emitters:

- Calculated the FEP efficiency for each emitter (slide 12)
- Interpolate the different FEP values

(Several) multiple gamma-ray emitter(s):

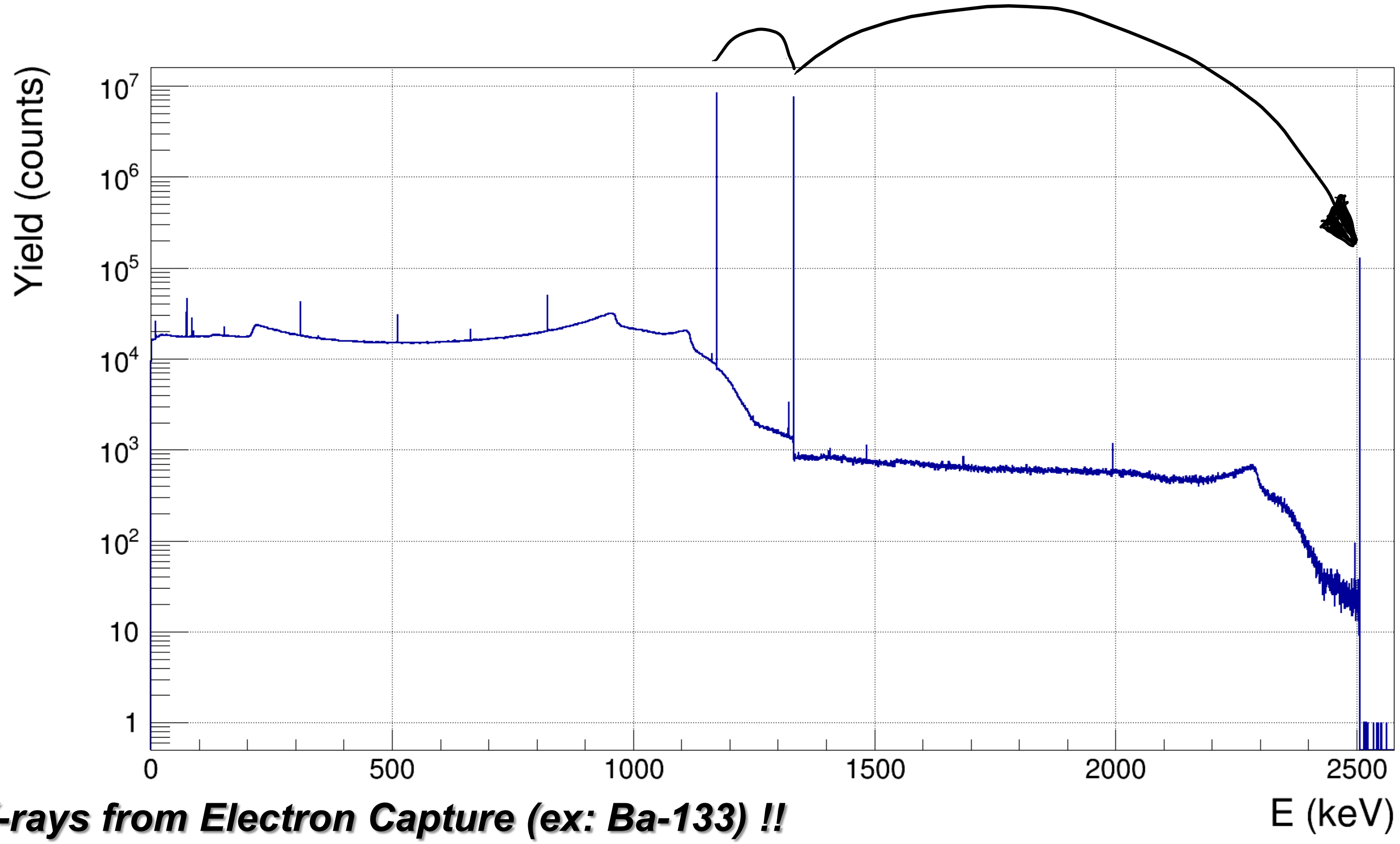
- Calculated the FEP efficiency for each emitter (slide 12)
- ! Check for possible interferences !
- ! Correct for possible coincidence summing effect !
- Interpolate the different FEP values

FEP efficiency curve: coincidence summing effect



Decay data Co-60, Decay Data Evaluation Project,
http://www.lnhb.fr/nuclides/Co-60_tables.pdf

Multiple gamma-ray emitters



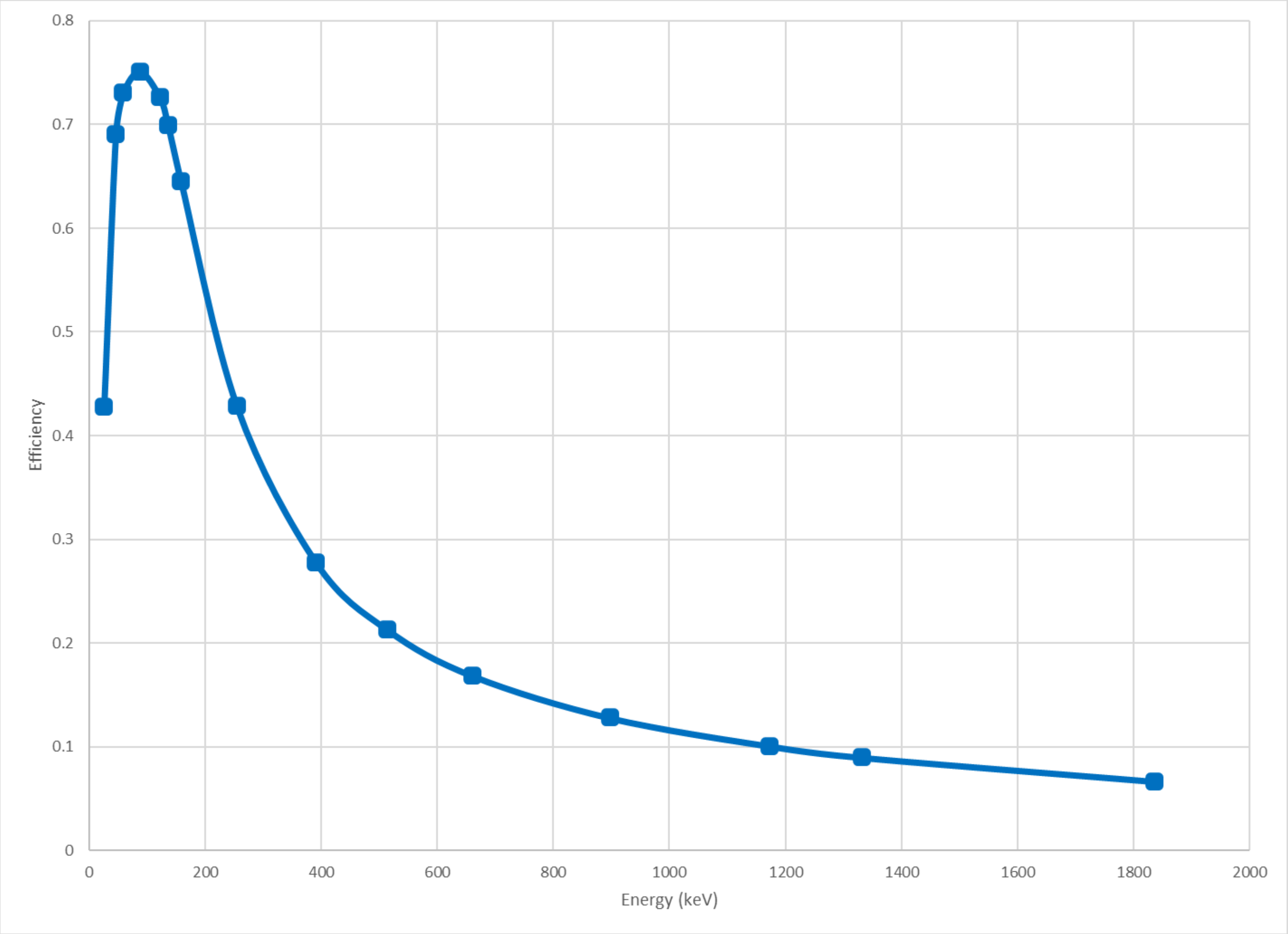
!! Also X-rays from Electron Capture (ex: Ba-133) !!

FEP efficiency curve: coincidence summing effect

Well type HPGe detector

FEP efficiencies **corrected** for coincidence summing

Am-241, Pb-210, Sr-85, Cs-109, Cs-137, Co-57, Te-123m, Sn-113, Co-60, Y-88



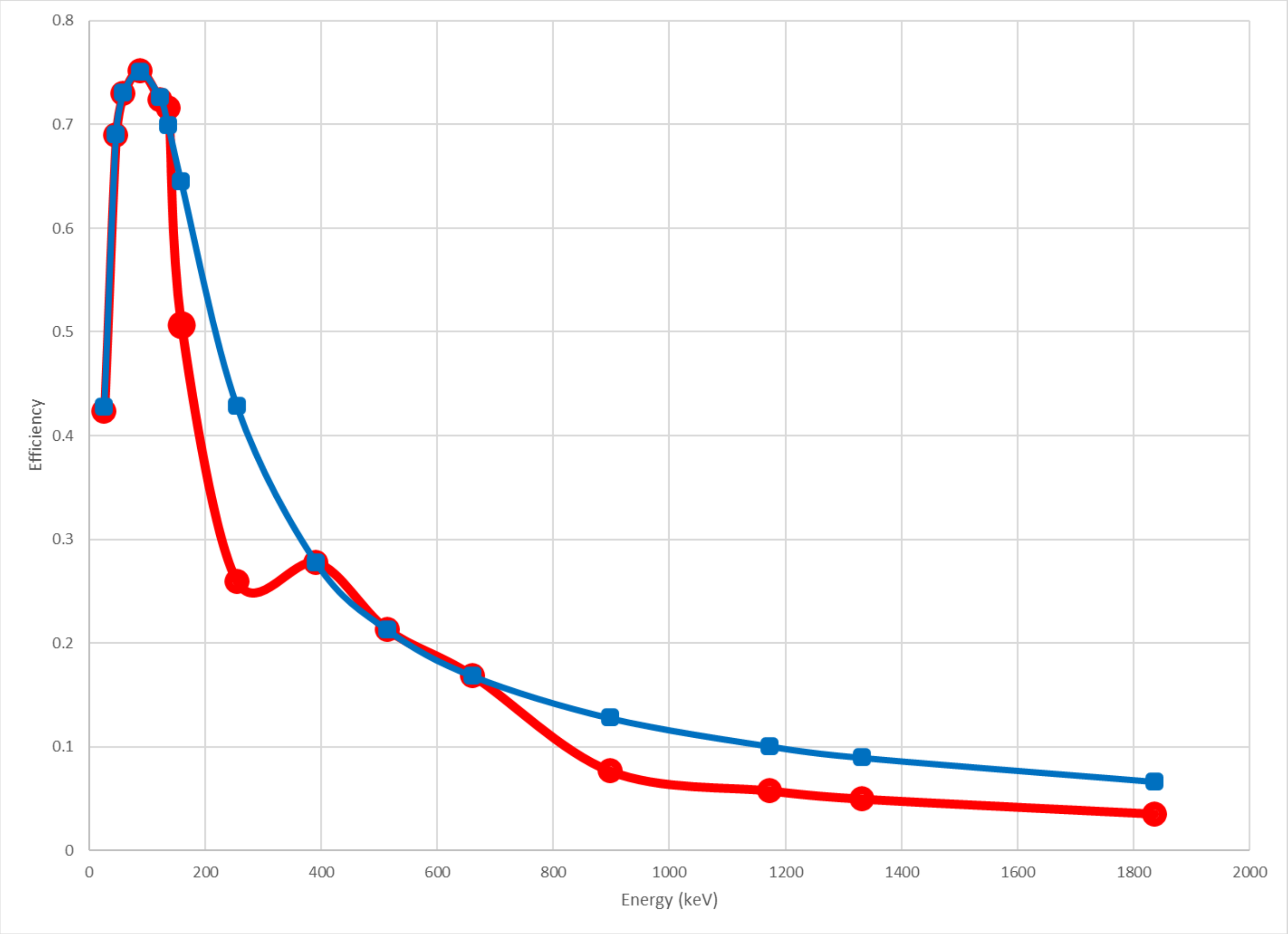
FEP efficiency curve: coincidence summing effect

Well type HPGe detector

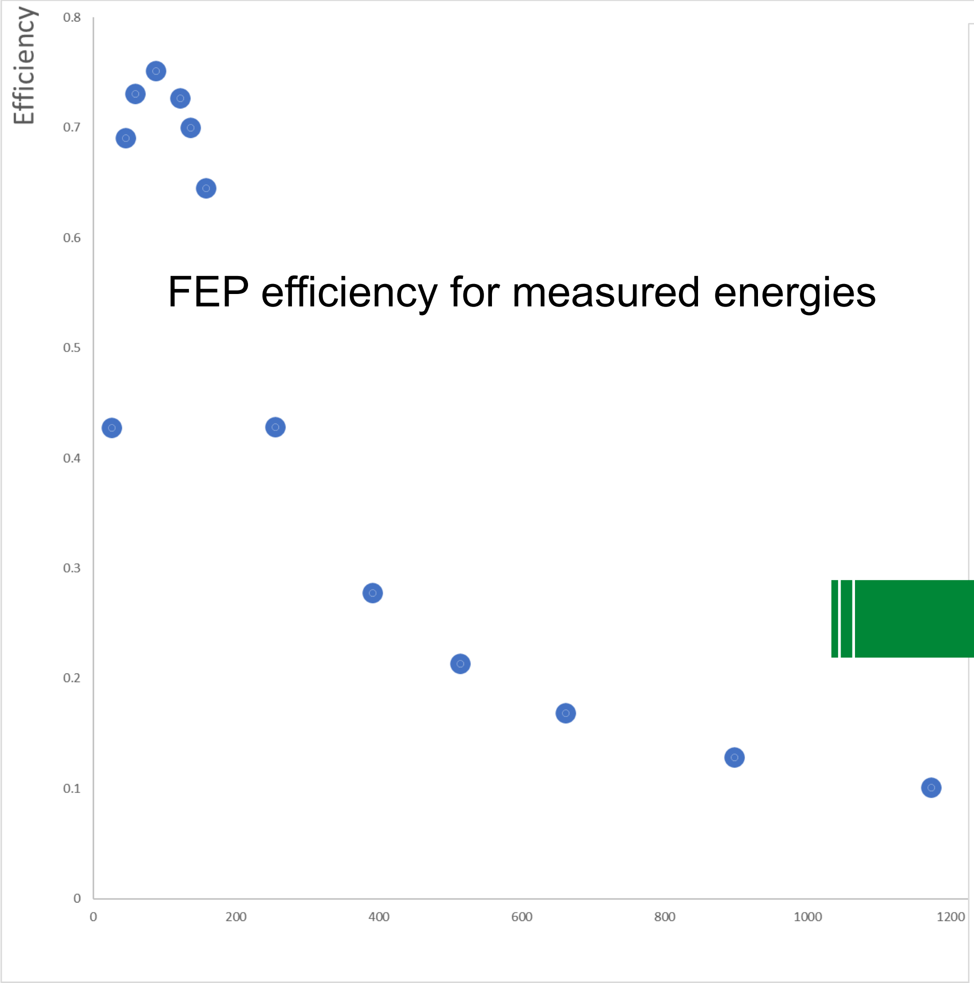
FEP efficiencies **corrected** for coincidence summing

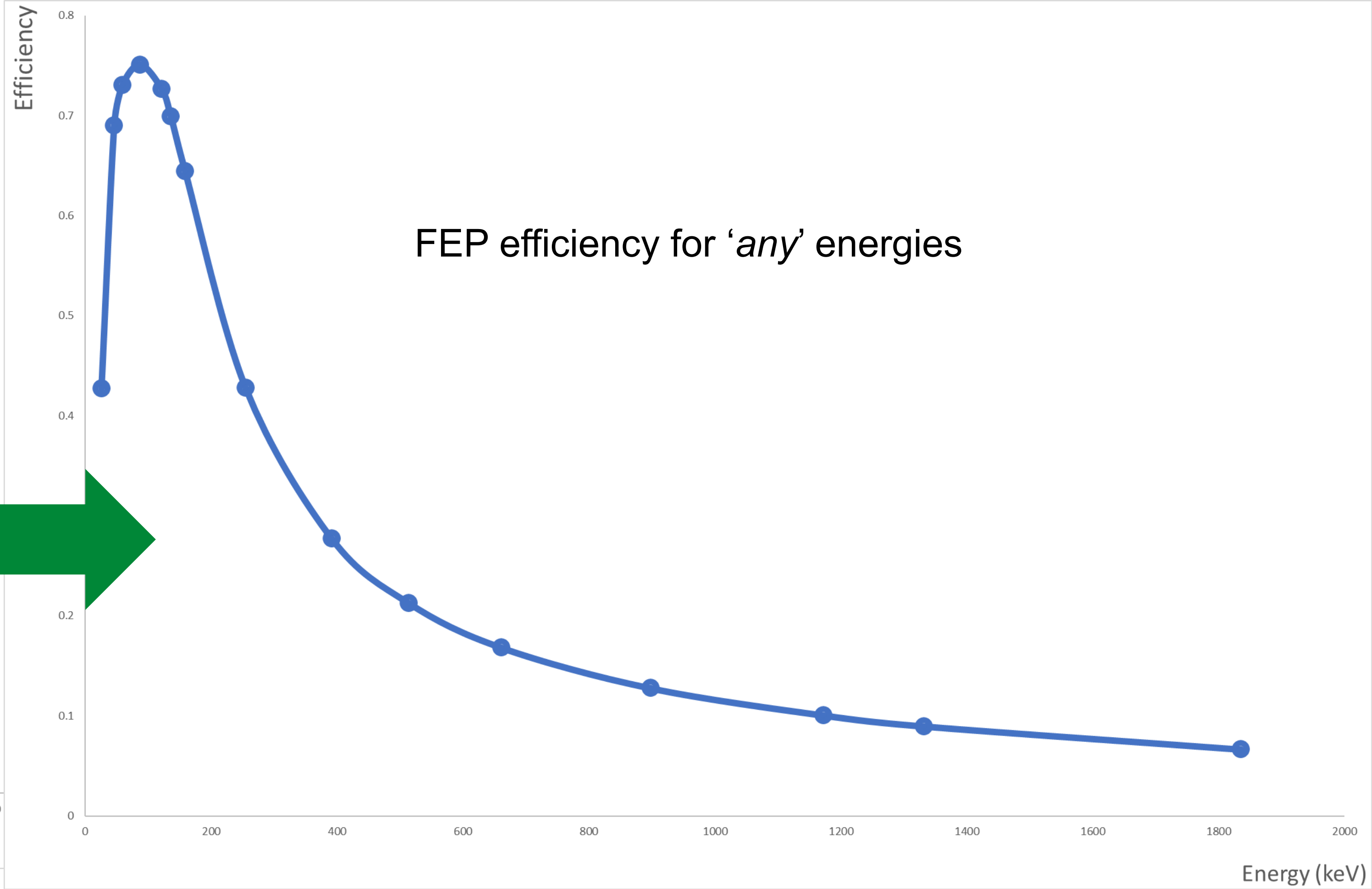
FEP efficiencies **not** corrected for coincidence summing

Am-241, Pb-210, Sr-85, Cs-109, Cs-137, Co-57, Te-123m, Sn-113, Co-60, Y-88

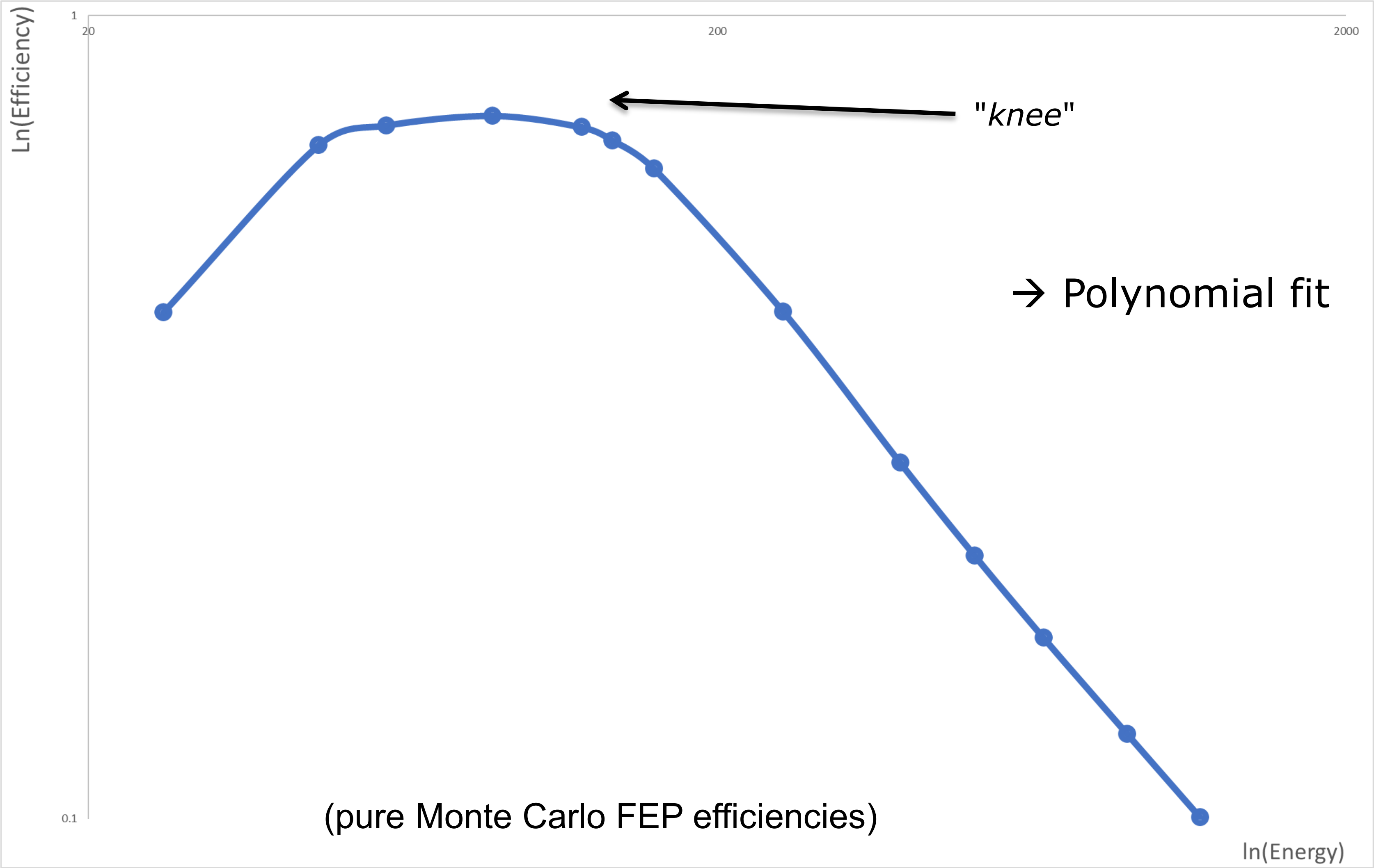


FEP efficiency curve: Interpolation





FEP efficiency curve: Interpolation



FEP efficiency curve: Examples of function

- so-called "*empirical*" (Mirion Genie 2000)

$$\ln \varepsilon(E) = \sum_{i=0}^{n} a_i \times \left(\ln \frac{X}{E}\right)^i$$

with $X = \frac{E_{min}+E_{max}}{2}$

a_i, b_i are calculated using Least squares method

- so-called "*dual*" (Mirion Genie 2000)

Split the data in 2 parts: below the "knee" and above

$$\ln \varepsilon(E)_{low} = \sum_{i=0}^{n} a_i \times (\ln E)^i$$

$$\ln \varepsilon(E)_{high} = \sum_{i=0}^{n} b_i \times (\ln E)^i$$

FEP efficiency curve: Examples of function

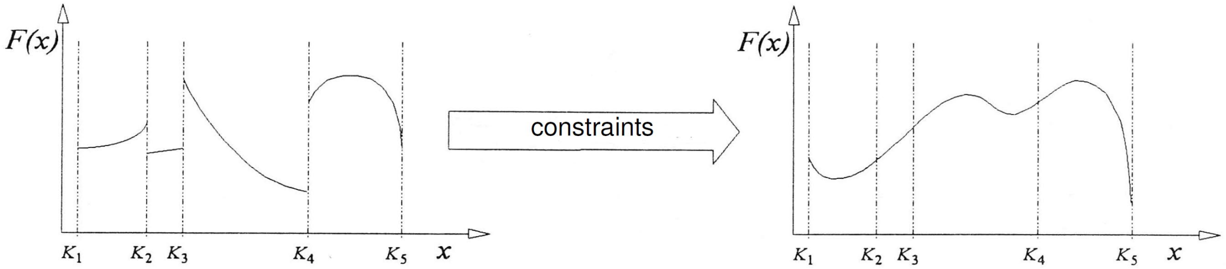
- so-called "*linear*" (Mirion Genie 2000)

$$\ln \varepsilon(E) = \sum_{i=0}^{n} a_i \times (E)^{-i}$$

a_i are calculated using Least squares method

- Spline interpolation

i. Divide the FEP efficiency in contiguous intervals
ii. Each interval is interpolated by a polynomial function
iii. Add constraints to the polynomial functions to get a continuous and smooth curve



(source: *Detection efficiency*, M-C Lépy, LNE-LNHB)

FEP efficiency curve: Interpolation function

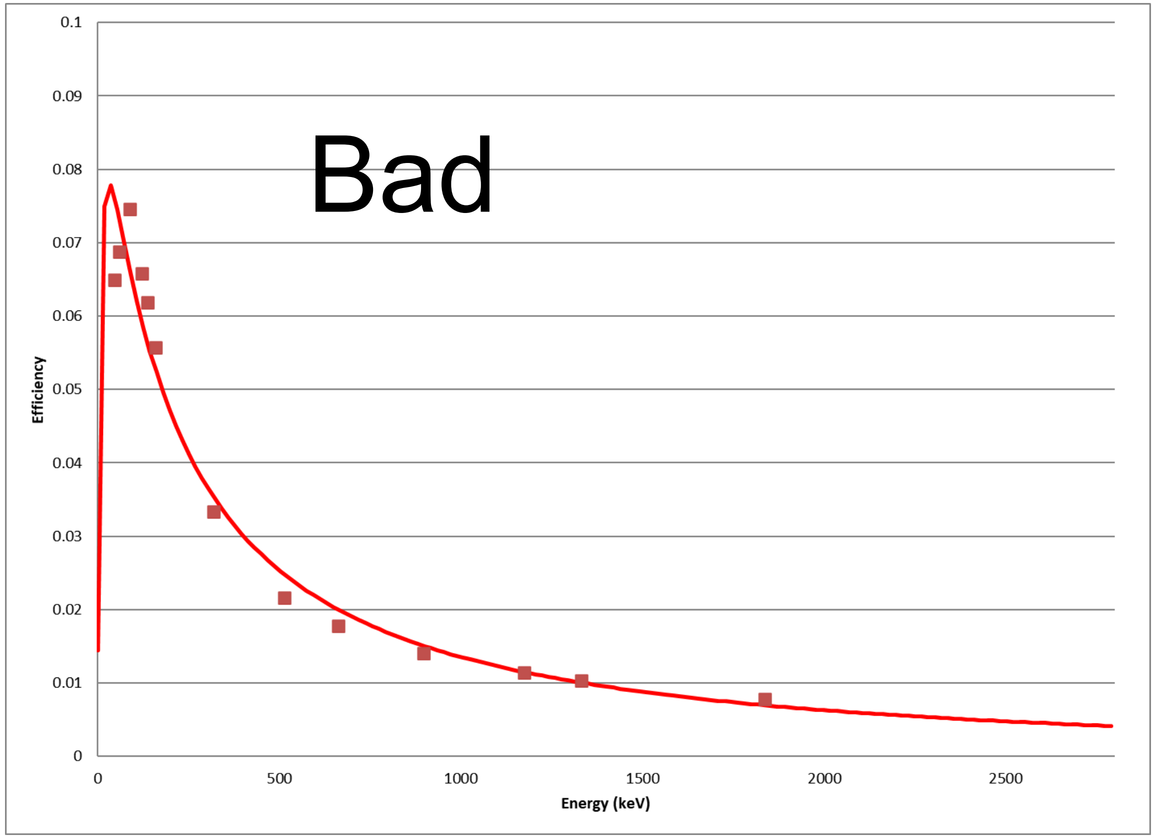
- No theoretical background behind the interpolation function, purely mathematical
- Experimental FEP efficiencies must by weighted (inverse of the associated uncertainty)
- Degree *n* of the polynomial function << number of FEP efficiencies

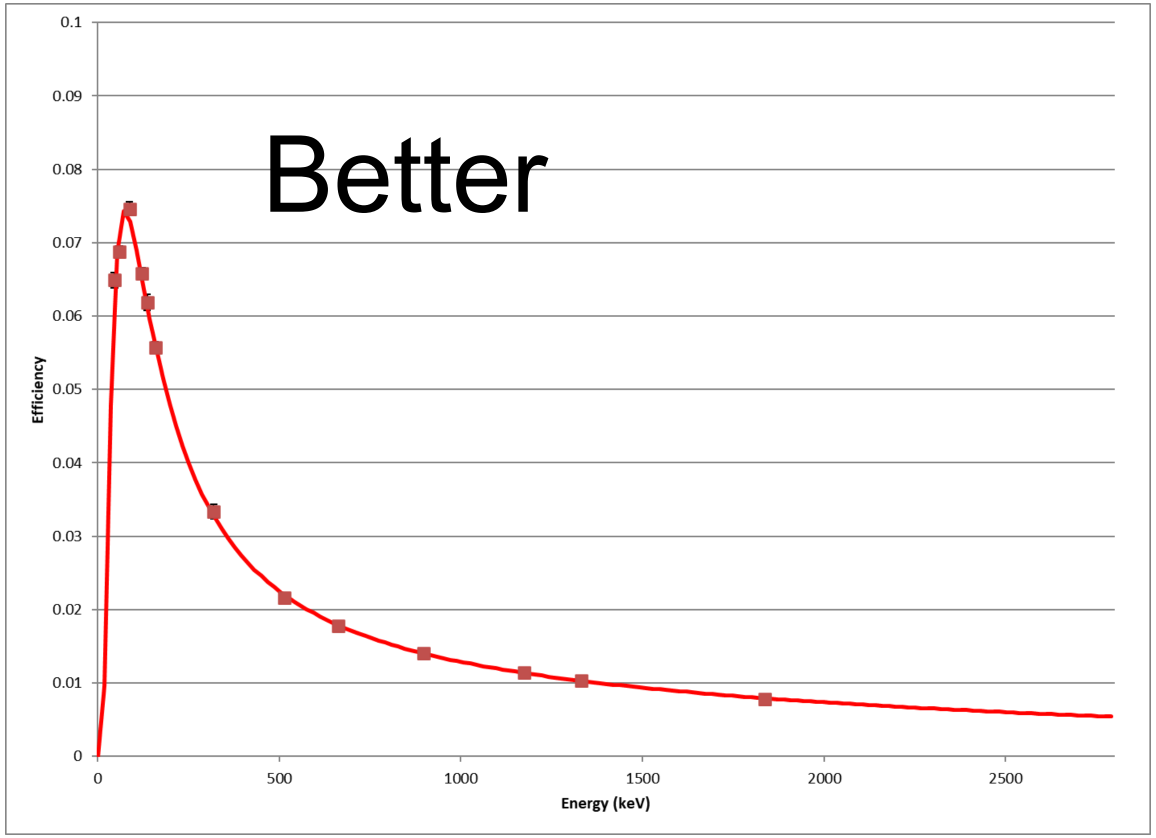
Example: by default, in Mirion Genie 2000

n=5, for 10 or more calibration points
n=4, for 8 or 9 calibration points
n=3, for 6 or 7 calibration points
n=2, for 3 to 5 calibration points

FEP efficiency curve: Check

Always do a visual check, don't trust the software !!!



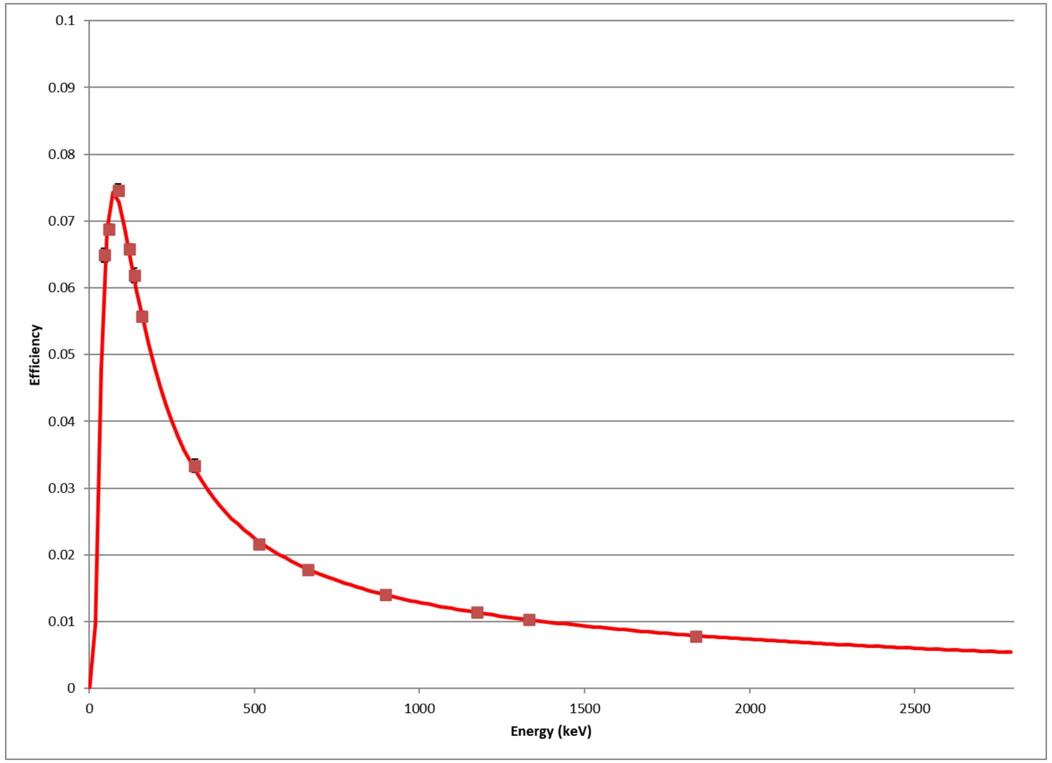


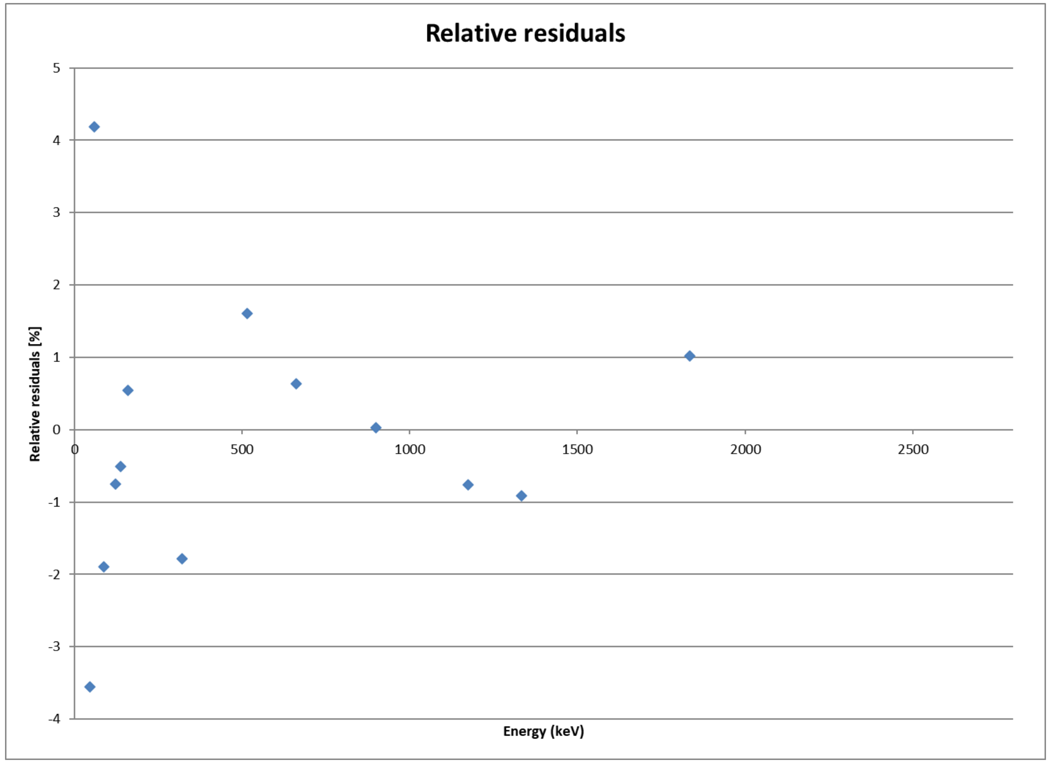
(real FEP efficiencies)

FEP efficiency curve: Validation

To qualify an interpolation function:

→ residuals = difference between the experimental values and the interpolated using the chosen function



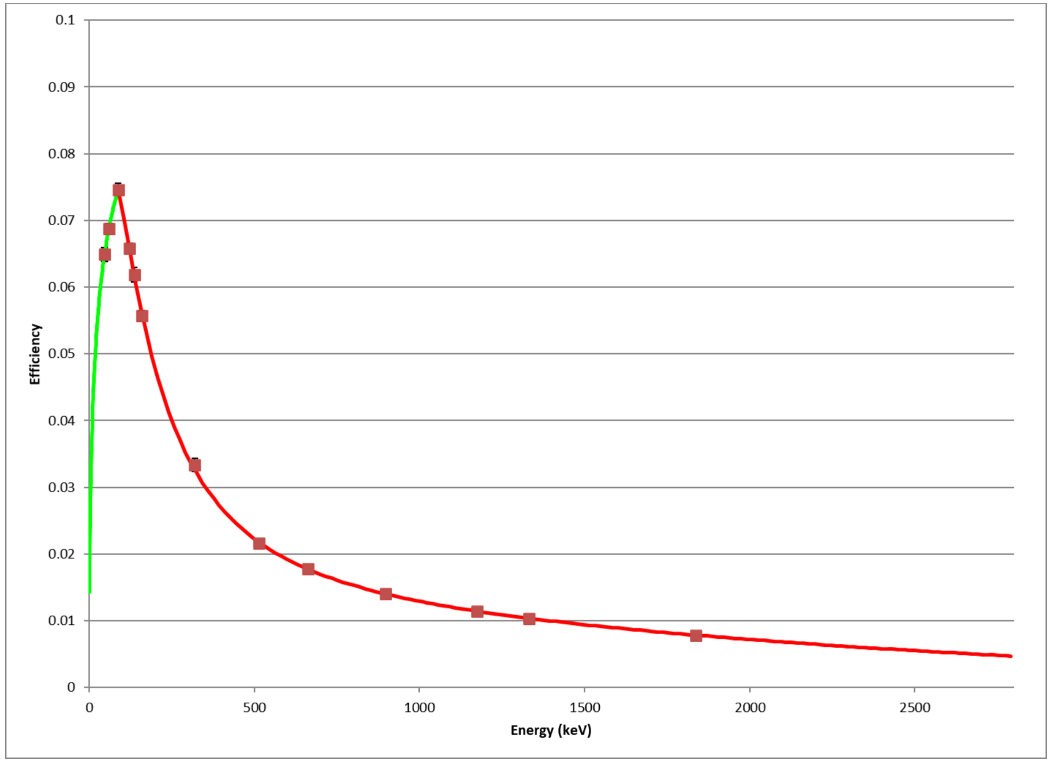


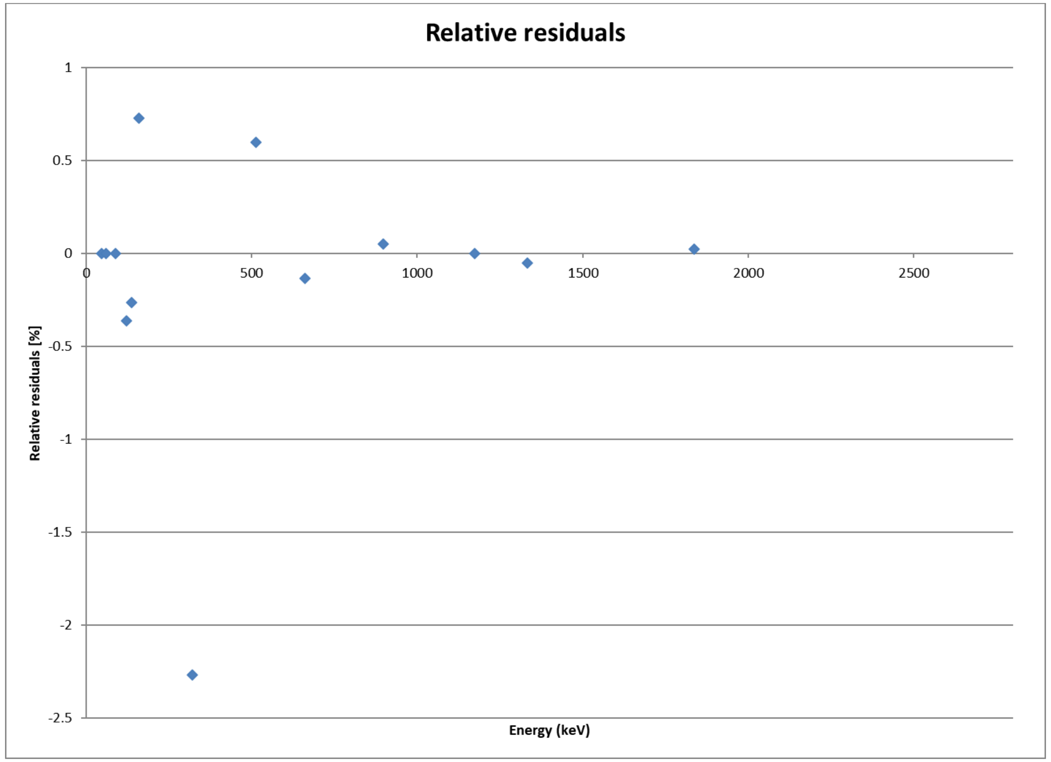
- ❑ Residuals should be distributed randomly
- ❑ As small as possible in your region of interest

FEP efficiency curve: Validation

To qualify an interpolation function:

→ residuals = difference between the experimental values and the interpolated using the chosen function

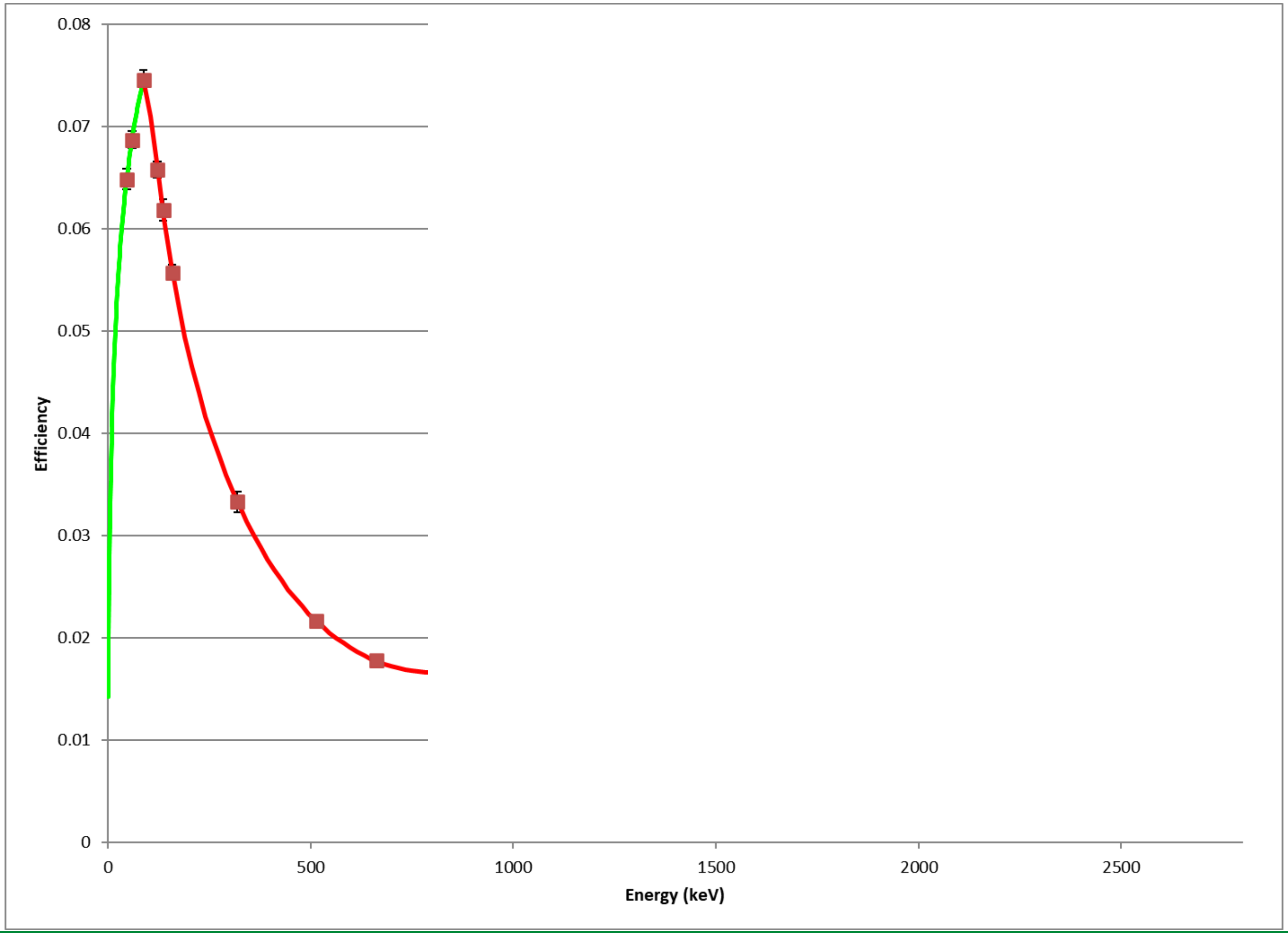




- ❑ Residuals should be distributed randomly
- ❑ As small as possible in your region of interest

FEP efficiency curve: Extrapolation

General rule: do not extrapolate !



FEP efficiency curve: Extrapolation

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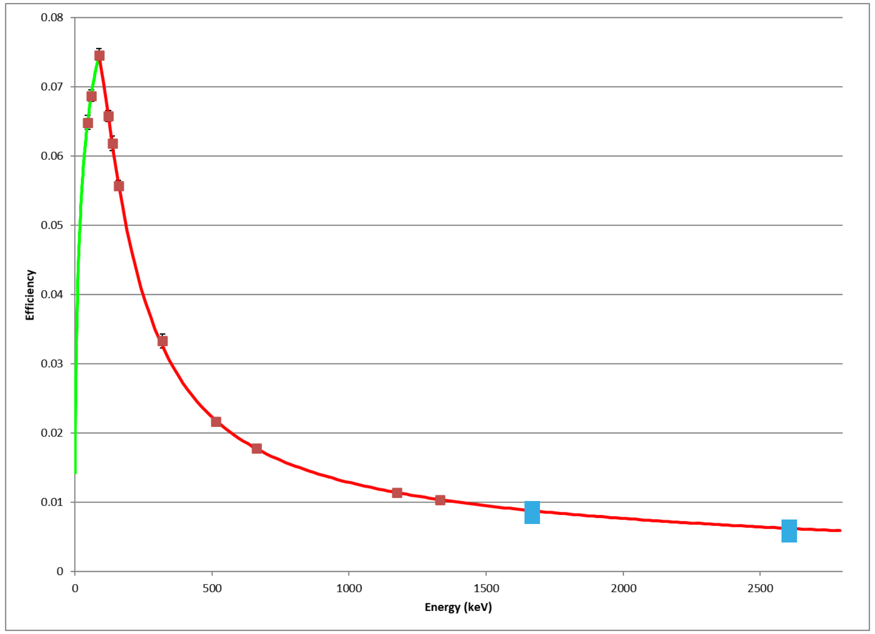
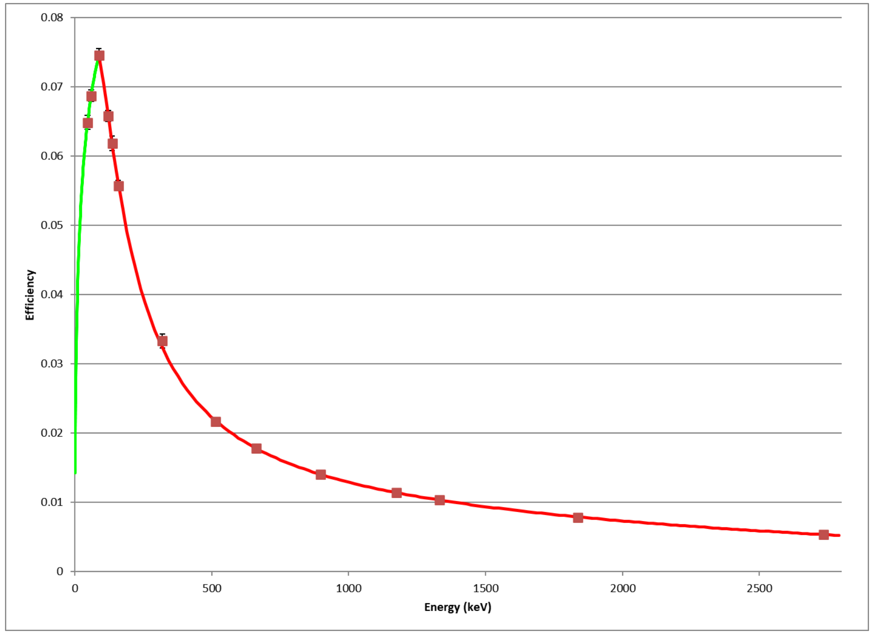




Fit:

ε(1836.1 keV) = 0.00821 (+5%)

ε(2734.1 keV) = 0.00601 (+11%)

Values:

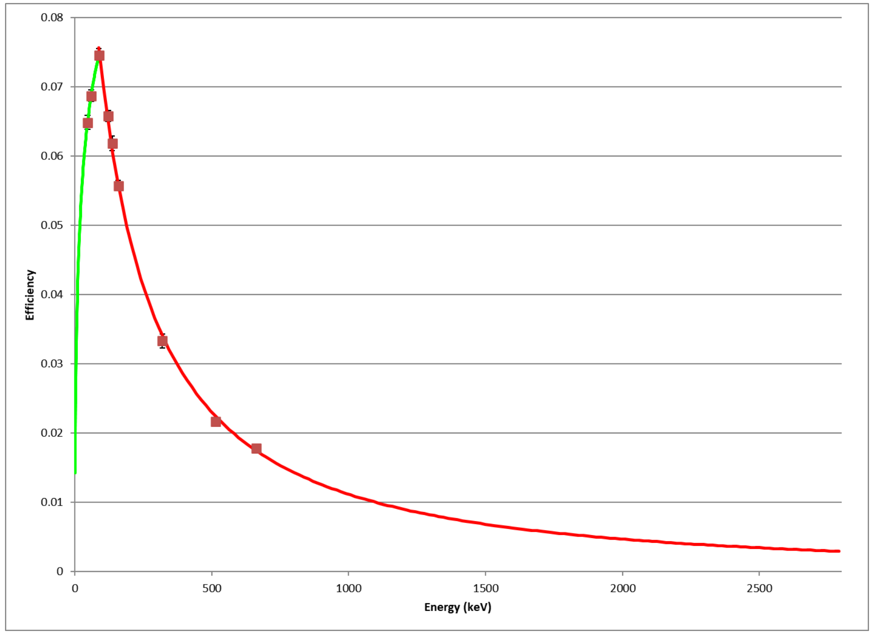
ε(1836.1 keV) = 0.00783

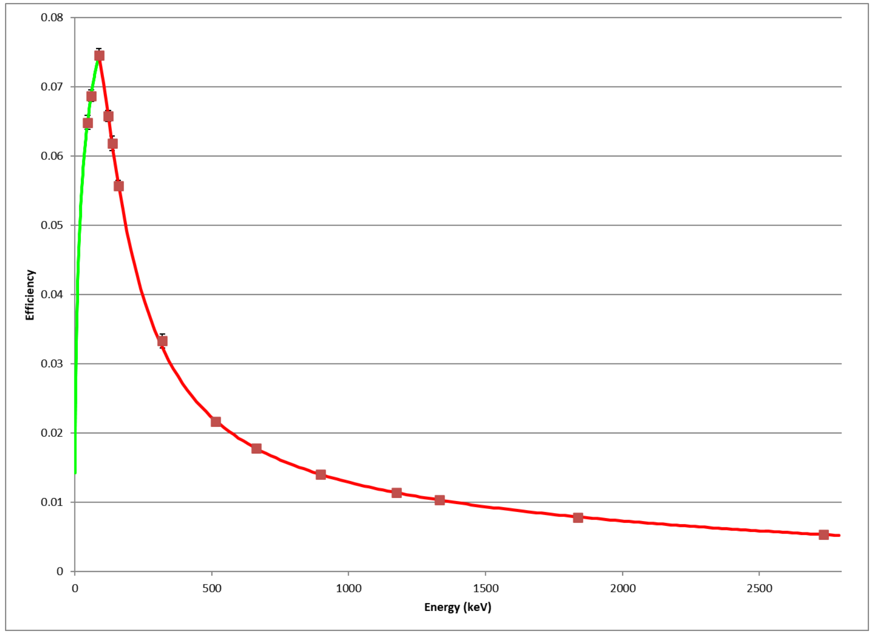
ε(2734.1 keV) = 0.00539

FEP efficiency curve: Extrapolation

General rule: do not extrapolate !

(Do it ‘**reasonably**’ and increase your uncertainty)





Fit:

ε(1836.1 keV) = 0.00528 (-33%)

ε(2734.1 keV) = 0.00304 (-44%)

Values:

ε(1836.1 keV) = 0.00783

ε(2734.1 keV) = 0.00539

Experimental way:

without calibration standard

No calibration standard available ??

Only ‘*Something active’* which has

Calibration source

❑ *different* composition

and/or

❑ *different* density

and/or

❑ *different* geometry

compared to your sample

and/or

❑ *other* distance

compared to your sample measurement

Maybe too different:

Efficiency transfer

Calibration source selection

- Geometry, composition and density as close as possible to the sample
- Select suitable radionuclides (same radionuclides as the sample, or radionuclides covering the energy range of interest)
- **Accredited laboratory**
- **SI traceable**
- Uncertainty on the reference value(s) as low as possible
  (~1% to < 5%, depending on radionuclide)

Efficiency Transfer method

1. Measure the calibration source

2. Calculate the associated FEP efficiencies ε_{source}

3. Interpolate the FEP efficiencies if needed

4. Correct $c_{corr}(E)$ the FEP efficiencies to take into account the different between your calibration source and your sample (+ distance sample/source to detector if relevant)

$$\varepsilon_{sample}(E) = \varepsilon_{source}(E) \times c_{corr}(E)$$

Calculation of the absolute peak efficiency of gamma-ray detectors for different counting geometries,

L. Moens et al., Nucl. Instr. and Meth. 187 (1981) 451.

Efficiency Transfer: Correction factor

Several software:

- ❑ Specialised computer code (commercial, free, open source):

  Mirion ISOCS/LabSOCS, EFFTRAN, ANGLE, GESPECOR, ETNA, DETEFF,…

- ❑ General purpose Monte Carlo codes

  Geant4, MCNP, EGSnrc, Penelope,…

Efficiency Transfer: Correction factor

Software need as input:

- Characteristics of the <u>detector</u>:
  - Type: planar, coaxial, well
  - Dimensions
  - Dead-layer thickness
  - Distance crystal-endcap
  - Thickness and material of the endcap
  - …

- Characteristics of the <u>calibration source</u> and <u>sample</u>:
  - Geometry, composition, density
  - Distance from the detector
  - …

Information sheet from manufacturer should be enough ☺

DETECTOR SPECIFICATION AND PERFORMANCE DATA
CERTIFICATE OF CONFORMITY

Specifications

Detector Model BE5030P — **Serial number** b 23049
Cryostat Model 7500SL-RDC-6-ULB — Order number [illegible]
Preamplifier Model iPA-SL

The purchase specifications and [illegible] ance of this detector are as follows :

Energy	[illegible]	122 keV	1332.5 keV
[illegible]	425	675	1800

Cryostat description or Drawing Number if special 7500SL-RDC-6-ULB

Physical Characteristics

Active Diameter 80.6 mm — Distance from window (outside) 5 mm
Active Area 5000 mm² — Window thickness 0.6 mm
Thickness 32 mm — Window material Carbon Epoxy

Electrical Characteristics

Depletion voltage (+) 2500 Vdc
Recommended bias voltage Vdc (+) 3500 Vdc
Reset rate at recommended bias / sec (PO preamp only)
Preamplifier test point voltage at recommended bias - 0.8 Vdc (RC preamp only)
Preamplifier output polarity Neg.

Resolution and Efficiency

With amp time constant of 4 µs - 7.2 µs Rise Time , 0.8 µs Flat Top

Isotope	^{55}Fe	^{57}Co	^{60}Co
Energy (keV)	5.9	122	1332.5
FWHM (eV)	368	610	1745
FWTM (eV)		1119	3220

Cooldown time 14 h
Coldtip setpoint (if CP5 config) : _____°C
- Tests are performed following IEEE standard test ANSI/IEEE std325-1996
- Standard Canberra electronics used - See Germanium detector manual Section 7

Efficiency Transfer: software example

EFFTRAN

Detector

Crystal diameter	60.00	mm	End cap (housing) diameter	80.00	mm
Crystal length	60.00	mm	End cap (housing) thickness	1.00	mm
			End cap (housing) material	aluminium	
Bulletization (crystal rounding) radius	0.00	mm			
Top dead layer	1.00	mm	Window thickness	1.00	mm
Side dead layer	1.00	mm	Window-to-crystal gap	5.00	mm
			Window material	aluminium	
Crystal hole (cavity) length	40.00	mm			
Crystal hole (cavity) diameter	10.00	mm			
			Mount cup (holder) thickness	0.00	mm
Crystal material	Ge		Mount cup (holder) material	aluminium	
			Absorber diametre	100.00	mm
			Absorber thickness	0.00	mm
			Absorber material	copper	

Detector Load Store

All numerical values must be equal to or larger than zero.

No check of the (internal) consistency of the data is performed!

The **window-to-crystal gap** is the distance between the top dead layer of the crystal and the detector window.

The **crystal diametre** includes its side dead layer. Similarly, the **crystal length** includes its top dead layer.

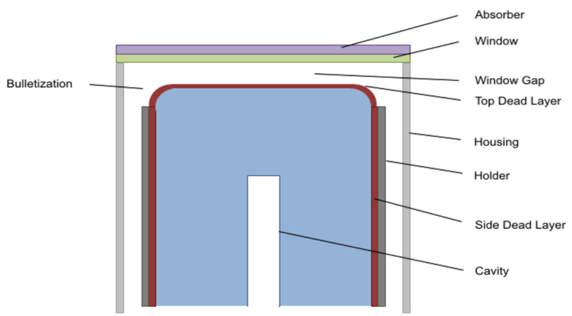
The upper edge of the crystal may be rounded. The amount of rounding is given in terms of the **bulletization (cystal rounding) radius**.

The **crystal hole** (**cavity**) is the central void drilled in the crystal, which contains the cooling pin (cold finger). The latter is not part of our model. The cavity diametre should include the surrounding germanium dead layer, which is also not modelled explicitly.

The **absorber** is assumed to be placed directly onto the detector window.

The crystal **mount cup** (**holder**) keeps the detector crystal in place.

The term **end cap** (**housing**) refers to the the detector cryostat, sometimes also called the detector can.



Source

	Standard		Sample	
Source filling height	30.00	mm	40.00	mm
Source material	water		water	
Container diameter	90.00	mm	90.00	mm
Containier bottom thickness	1.00	mm	1.00	mm
Container side wall thickness	1.00	mm	1.00	mm
Container material	polystyrene		polystyrene	
Container-to-absorber gap*	0.00	mm	0.00	mm

Standard: Load Store

Sample: Load Store

All numerical values must be equal to or larger than zero.

To simulate a point source, set all the numerical parameters to zero (except the container-to-absorber-gap) and all the materials to "vacuum" !

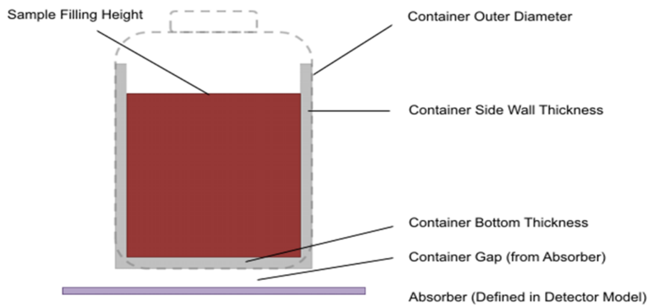
No check of the (internal) consistency od the data is performed!

The **container-to-absorber gap** is the distance between the top of the detector absorber and the bottom of the sample container.

The **sample filling height** refers to the sample material only, excluding the container bottom thickness.

The **container diametre** includes (both) its side walls.

The source material is assumed to tightly fill the space in the container in its radial dimension.



Efficiency Transfer: software example

EFFTRAN

Efficiency

E [keV]	Standard Efficiency	Uncertainty [%]	Sample Efficiency	Uncertainty [%]
44.0	8.035E-03	3.0	6.968E-03	3.1
55.0	1.167E-02	[illegible]	1.004E-02	[illegible]
80.0	1.651E-02	[illegible]	1.402E-02	[illegible]
100.0	1.836E-02	[illegible]	1.552E-02	[illegible]
120.0	1.844E-02	[illegible]	1.557E-02	[illegible]
150.0	1.699E-02	[illegible]	1.434E-02	[illegible]
200.0	1.377E-02	[illegible]	1.165E-02	[illegible]
300.0	9.263E-03	[illegible]	7.867E-03	[illegible]
400.0	7.053E-03	[illegible]	6.010E-03	[illegible]
500.0	5.720E-03	[illegible]	4.887E-03	[illegible]
600.0	4.819E-03	[illegible]	4.126E-03	[illegible]
800.0	3.678E-03	[illegible]	3.159E-03	[illegible]
1000.0	2.982E-03	3.0	2.567E-03	3.1
1250.0	2.417E-03	3.0	2.086E-03	3.1
1500.0	2.033E-03	3.0	1.757E-03	3.1
1750.00	1.757E-03	3.0	1.521E-03	3.1

$\varepsilon_{source}(E)$

Transfer Efficiency

from Standard to Sample

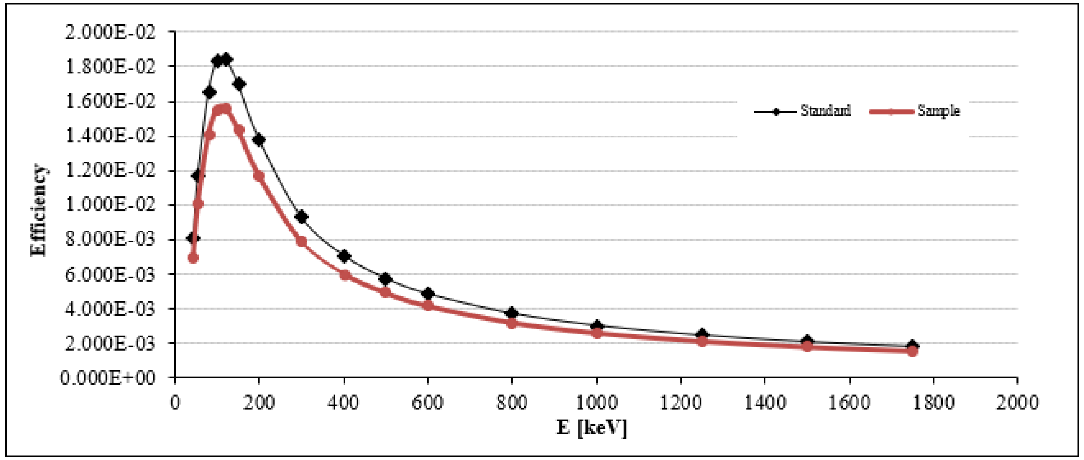
$\varepsilon_{sample}(E)$ → FEP curve of the sample

Import

Standard Efficiency from a Canberra CAL file

Export

Sample Efficiency to EFFTRAN.CAL



Efficiency Transfer: Calculation method

Software generate a computer model using the input data given

- Effective solid angle method

$$\varepsilon(E) \approx \int_{\Omega} \prod_{i} \left(e^{-\mu_i(E).x_i}\right) \times \left(1 - e^{-\mu_d(E).x_d}\right) \times P_{tot}(E) \times d\Omega$$

$$\varepsilon'(E) = \varepsilon_0(E) \times \frac{\boldsymbol{\bar{\Omega}_{sample}(E)}}{\boldsymbol{\bar{\Omega}_{calib}(E)}}$$

Calculations using semi-empirical equations of the solid angles taking into account attenuations

- Monte Carlo method

$$\varepsilon'(E) = \varepsilon_0(E) \times \frac{\boldsymbol{\bar{\varepsilon}_{sample}(E)}}{\boldsymbol{\bar{\varepsilon}_{calib}(E)}}$$

Calculate the FEP efficiency of the calibration source $\bar{\varepsilon}_{calib}(E)$ and the sample $\bar{\varepsilon}_{sample}(E)$

Efficiency transfer: Remarks

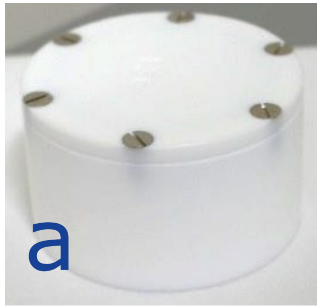
- Check results from your calibration source using the calibration source $(c_{corr}(E) = 1)$
- Validate efficiency transfer using other source(s), samples from previous proficiency tests,…
- Specialised computer code are usually very fast but can have several limitations
- General purpose software need more to time to set up and computation time can be long but have less limitations
- Check if the software includes coincidence summing corrections !!!
- Imperfections in the detector model cancel out, if the calibration source and sample have a close geometry
- Avoid efficiency transfer from point source to (volume) sample

Efficiency transfer: robustness

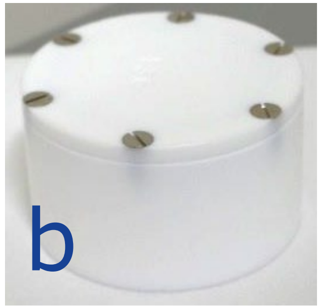
Example:

- spiked ^{131}I, ^{134}Cs, ^{137}Cs maize powder
- mass ~20 g
- water content (12.85± 0.02)%

- Measured on a coaxial HPGe detector on the endcap
- Efficiency transfer: 3 different calibration sources



Liquid solution with
^{133}Ba, ^{152}Eu, ^{60}Co, ^{134}Cs, ^{137}Cs



Resin with
^{210}Pb, ^{60}Co, ^{137}Cs, ^{241}Am, ^{133}Ba, ^{109}Cd, ^{139}Ce, ^{57}Co, ^{51}Cr, ^{113}Sn, ^{85}Sr, ^{88}Y

Efficiency transfer: robustness

Massic activity per dry mass (Bq/kg)

Nuclide	Liquid solution Teflon (a)	Resin Teflon (b)	Resin Nalgene (c)	Rel. standard deviation (%)
^{131}I	199 ± 7	198 ± 6	197 ± 6	**0.5**
^{134}Cs	922 ± 28	910 ± 30	890 ± 31	**1.2**
^{137}Cs	566 ± 18	560 ± 19	550 ± 19	**1.4**
^{40}K	106 ± 8	105 ± 7	102 ± 7	**2.3**

Computer simulation

Monte Carlo modelling

→ After tomorrow

Comments

- FEP efficiency are only valid for a given configuration and for a specific gamma-ray energy

- Experimental FEP efficiencies/curves can be corrected to the sample configuration using Efficiency Transfer method

- Re-do/check the FEP efficiency calibration after a repair of the detector

- Re-do/check the FEP efficiency calibration after a long warming up of the detector

(dead-layer may have increased by diffusion)

- Check the FEP efficiency calibration frequently → stability of the detector

- Place the sample/standard/source at a well-defined position using holder(s)