# Activity standardization by photon-photon coincidence methods

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# Outline

- Introduction
  - Becquerel
  - Activity standardization

- Coincidence methods
  - Gamma-gamma coincidence
  - $^{60}Co$ example
  - $^{125}I$ example

- Conclusion

# Activity standardization

*“The activity, A, of an amount of a radionuclide in a particular energy state at a given time is the quotient of -dN by dt, where dN is the mean change in the number of nuclei in that energy state due to spontaneous nuclear transformations in the time interval dt, thus A = -dN/dt.*

*Unit: $s^{-1}$. The special name for the unit of activity is becquerel (Bq).”*

(ICRU, 2011)

Standardization methods:

- The high-geometry (4π) systems
- Defined solid angle counting
- Coincidence counting methods

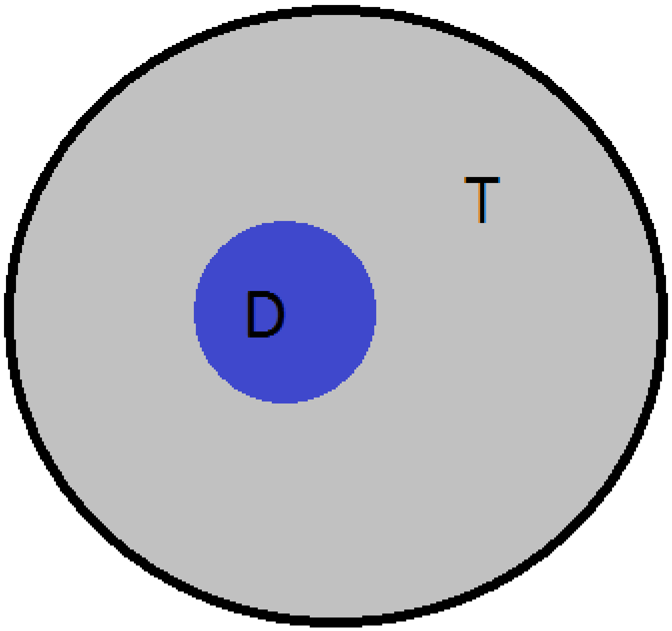


Pommé, S., 2007. Methods for primary standardization of activity. Metrologia 44, S17–S26.

# What is efficiency?

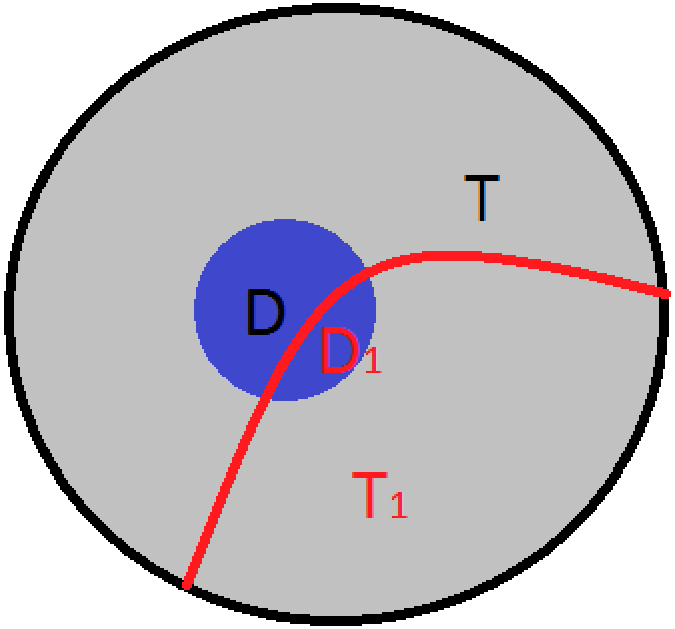
$$\varepsilon = \frac{D}{T}$$

$$\varepsilon_{FEP} = \frac{D(in\,peak)}{T}$$

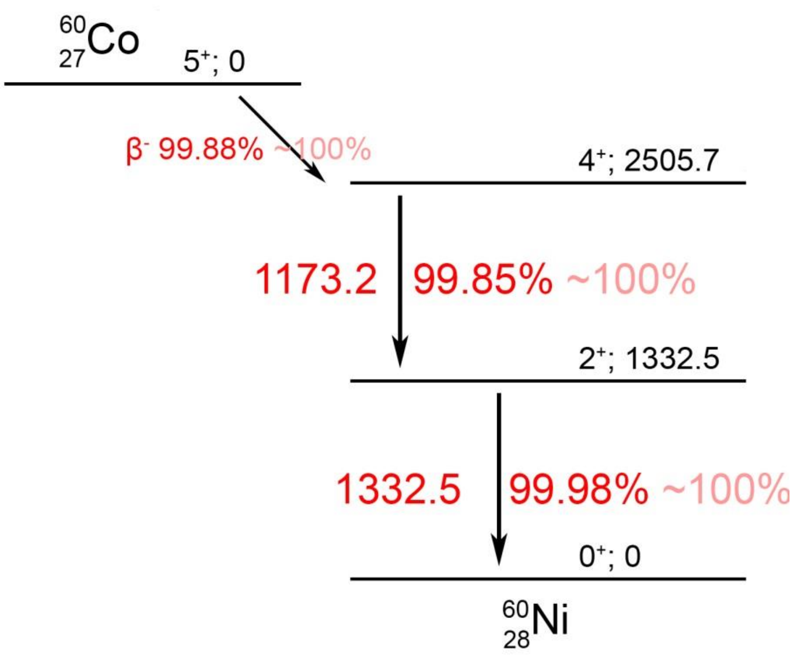


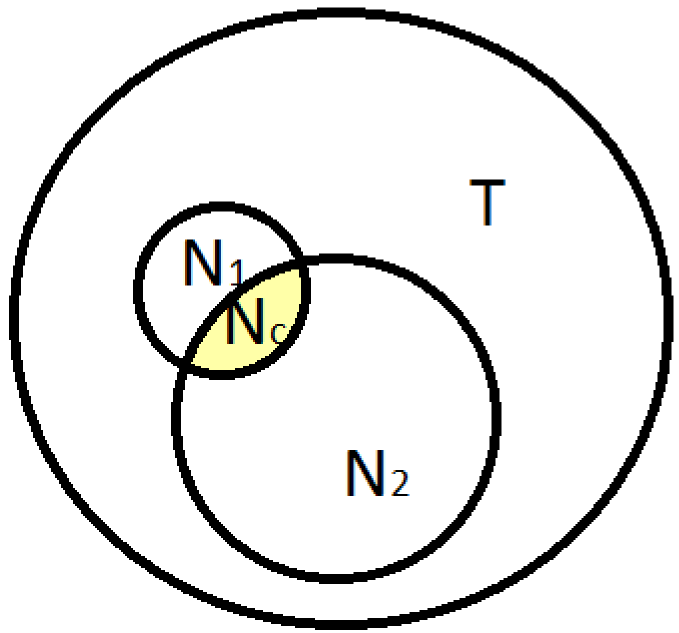
# What is efficiency?

$$\varepsilon = \frac{D}{T} = \frac{D_1}{T_1}$$



# Coincidence method: Co-60




N1 –detected by detector 1

N2 – detected by detector 2

Nc – coincident detection by both detectors

$$\varepsilon_1 = \frac{N_1}{T} = \frac{N_c}{N_2}$$

# Absolute activity determination: Co-60

γ-γ coincidence simplified version:

$N_1$ – number of counts in 1173 keV peak on detector 1:

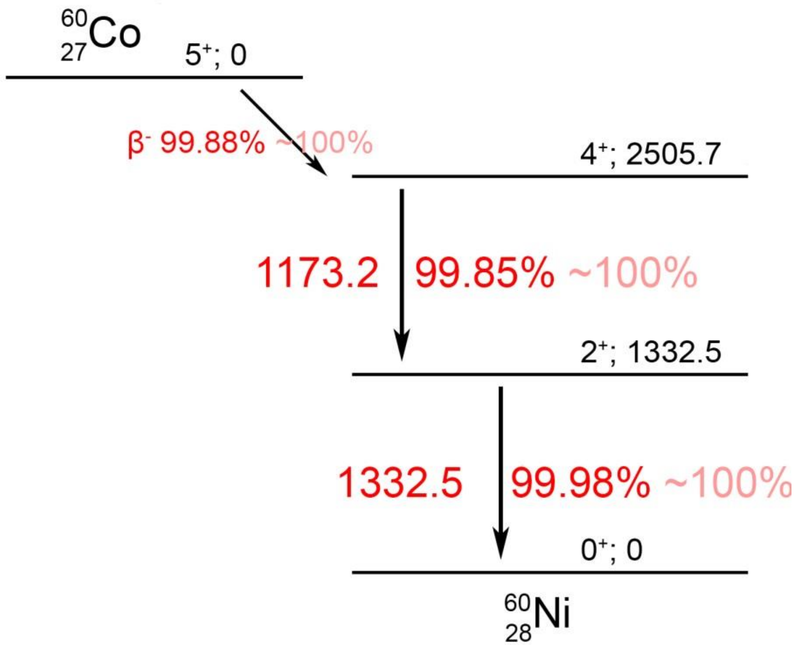
$$N_1 = N_0 * \varepsilon_1$$

$N_2$– number of counts in 1332 keV peak on detector2:

$$N_2 = N_0 * \varepsilon_2$$

Coincidence peak count rates:

$$N_c = N_0 * \varepsilon_1 \ * \varepsilon_2 \ * W(\theta)$$




$\varepsilon_1 = N_1/N_0$

$\varepsilon_2 = N_2/N_0$

$$N_0 = \frac{N_1 N_2}{N_c} * W(\theta)$$

$$\varepsilon_2 = \frac{N_c}{N_1 * W(\theta)}$$

↔

$$\varepsilon = \frac{\text{N(photons detected in the peak)}}{\text{N(photons emitted from the source)}}$$

# Absolute activity determination: Co-60

$$N_1 = N_0 * X_1 \varepsilon_1^{1,p}\left(1 - X_2 \varepsilon_1^{2,tot}\right)$$

$$N_2 = N_0 * X_2 \varepsilon_1^{2,p}\left(1 - X_1 \varepsilon_1^{1,tot}\right)$$

$$N_3 = N_0 * X_1 \varepsilon_2^{1,p}\left(1 - X_2 \varepsilon_2^{2,tot}\right)$$

$$N_4 = N_0 * X_2 \varepsilon_2^{2,p}\left(1 - X_1 \varepsilon_2^{1,tot}\right)$$

Single count rates in photopeak i (i=1, 2)

$$N_5 = N_0 * X_1 \varepsilon_1^{1,p} X_2 \varepsilon_2^{2,tot}$$

$$N_6 = N_0 * X_2 \varepsilon_1^{2,p} X_1 \varepsilon_2^{1,tot}$$

$$N_7 = N_0 * X_1 \varepsilon_2^{1,p} X_2 \varepsilon_1^{2,tot}$$

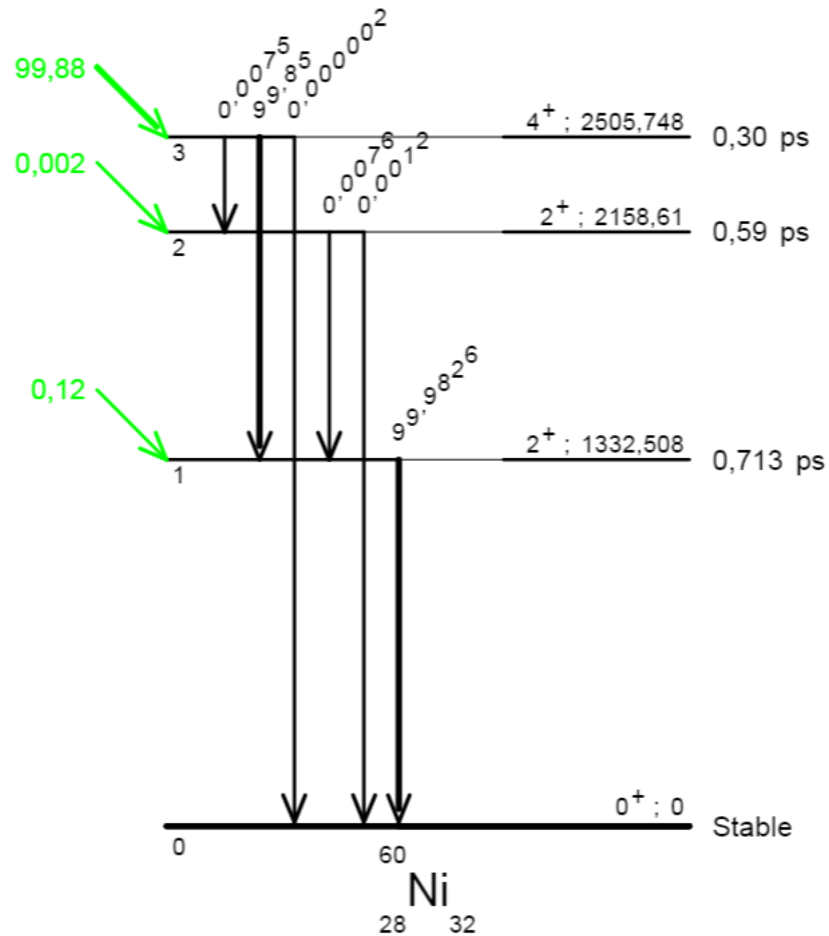
$$N_8 = N_0 * X_2 \varepsilon_2^{2,p} X_1 \varepsilon_1^{1,tot}$$

Coincidence peak (i=1, 2) count rates

$$N_9 = N_0 * X_1 \varepsilon_1^{1,p} X_2 \varepsilon_1^{2,p}$$

$$N_{10} = N_0 * X_2 \varepsilon_2^{1,p} X_1 \varepsilon_2^{2,p}$$

Sum peak count rates




$$N_{01} = \frac{(N_1N_3 - N_5N_7)(N_2N_4 - N_6N_8)}{N_9(N_3 - N_7)(N_4 - N_8)}$$

$$N_{02} = \frac{(N_1N_8 - N_5N_7)(N_2N_4 - N_6N_8)}{N_{10}(N_1 - N_5)(N_2 - N_6)}$$

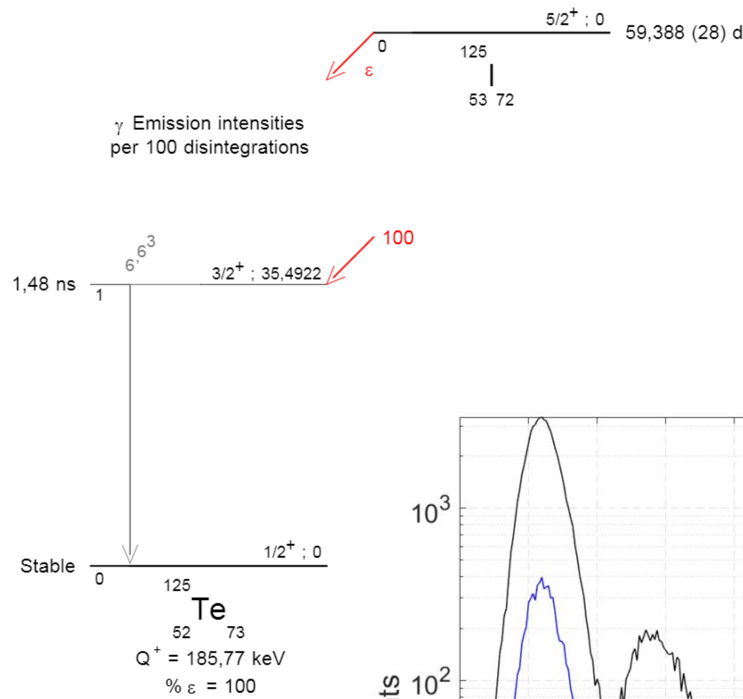
$$N_0 = \sqrt{N_{01}N_{02}}$$



Volkovitsky, P., Naudus, P., 2009. Nucl. Inst. Methods Phys. Res. A 607, 568–572.

# $^{125}$I NaI(Tl)-NaI(Tl)

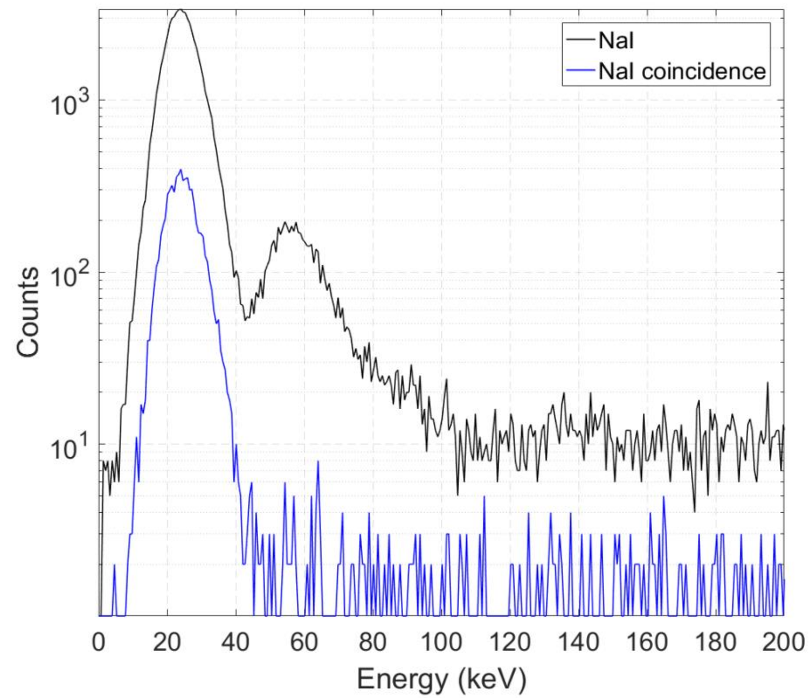
Primary standardization method.




$$N_1 = N_0\{X_1 + X_2 - X_1X_2\varepsilon_1\}\varepsilon_1$$
$$N_2 = N_0\{X_1 + X_2 - X_1X_2\varepsilon_2\}\varepsilon_2$$
$$N_c = N_0\{2X_1X_2\}\varepsilon_1\varepsilon_2.$$

Solving three equations with two unknowns - eliminates detector efficiencies ε giving the sample activity $N_0$

$$\varepsilon_1 = \frac{X_1 + X_2}{X_1X_2}\left\{2(N_2/N_c) + \frac{2(N_2/N_c) - 1}{2(N_1/N_c) - 1}\right\}^{-1}.$$




Very accurate with uncertainties less than 0.3% reported.

# $^{125}$I HPGe-HPGe

Ge X-ray escape makes problems:

$$N_1 = N_0(X_\gamma \varepsilon_1^{\gamma,p} - X_\gamma \varepsilon_1^{\gamma,p} \times X_1 \varepsilon_1^{X,tot})$$

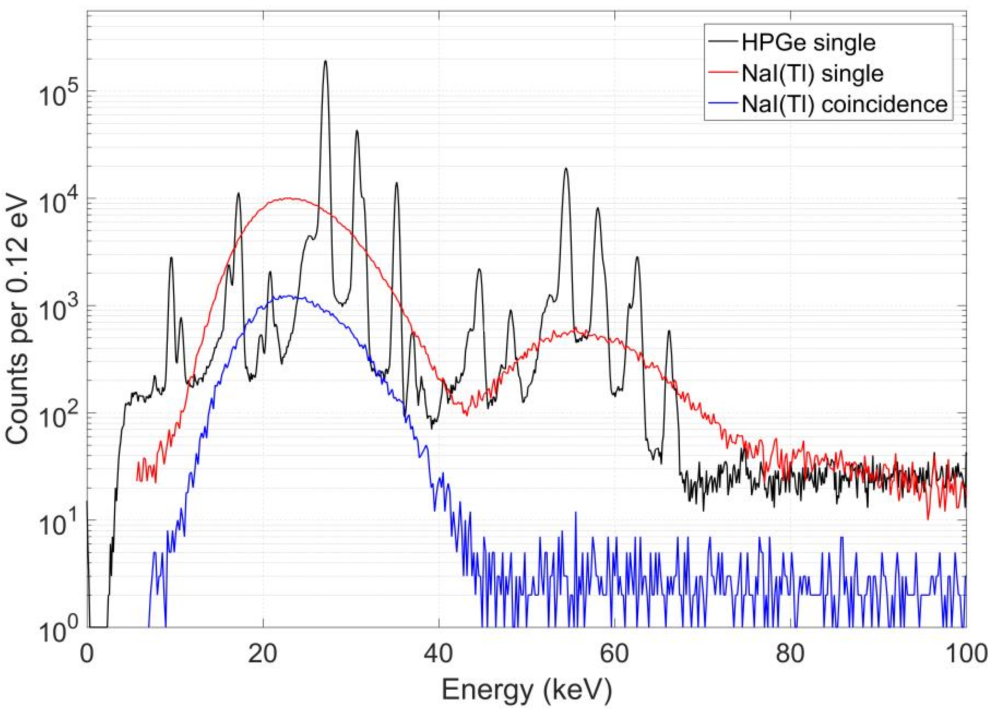
$$N_2 = N_0(X_\gamma \varepsilon_2^{\gamma,p} - X_\gamma \varepsilon_2^{\gamma,p} \times X_1 \varepsilon_2^{X,tot})$$

$$N_3 = N_0\, X_\gamma \varepsilon_2^{\gamma,p} \times X_2 \varepsilon_1^{X,p}$$

$$N_4 = N_0\, X_\gamma \varepsilon_1^{\gamma,p} \times X_2 \varepsilon_2^{X,p}$$

$$N_5 = N_0\, X_\gamma \varepsilon_1^{\gamma,p} \times X_1 \varepsilon_2^{X,\mathrm{tot}}$$

$$N_6 = N_0\, X_\gamma \varepsilon_2^{\gamma,p} \times X_1 \varepsilon_1^{X,\mathrm{tot}}$$




Additional assumption for analytical solution:

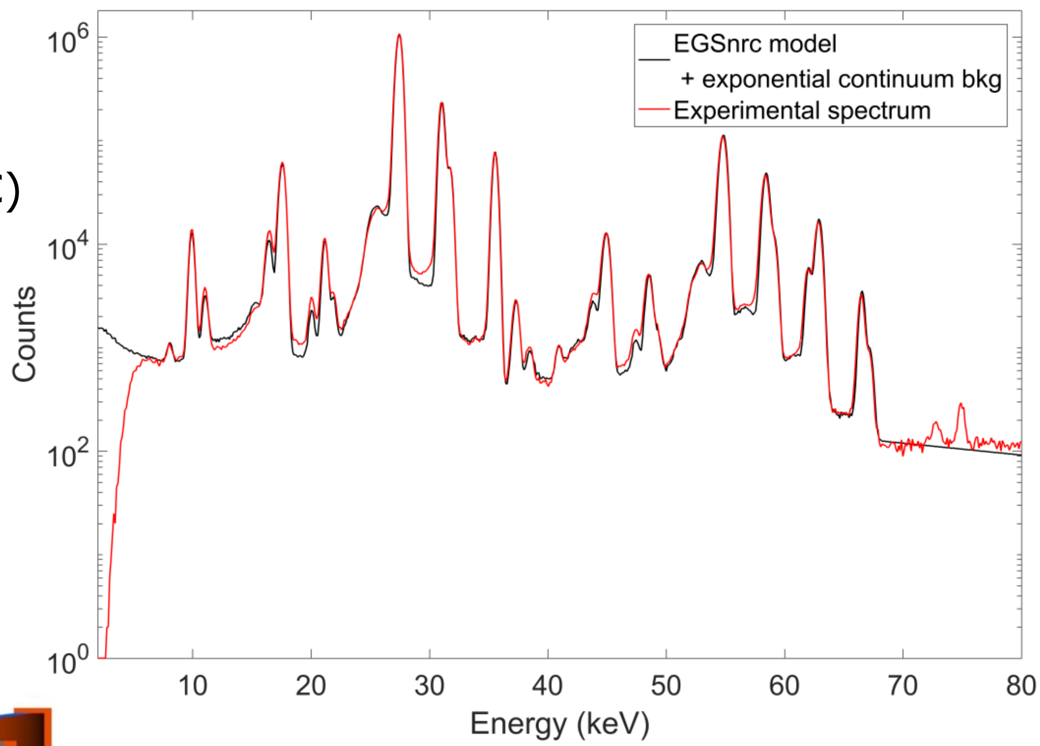
$$\varepsilon_1^{X,p} = z_1\, \varepsilon_1^{\gamma,p}$$

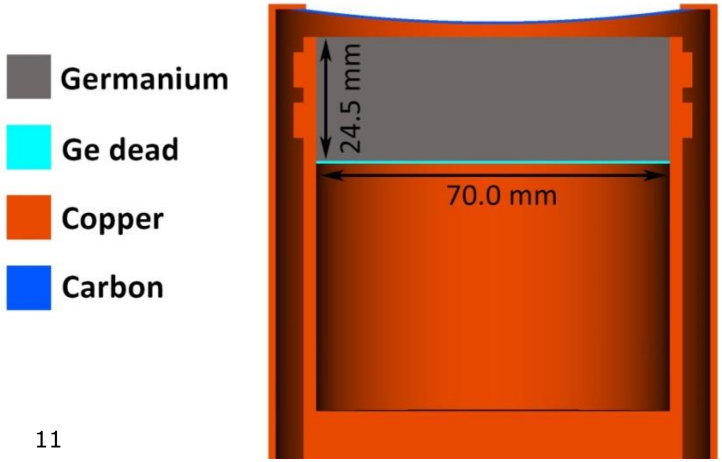
$$N_{01} = \frac{z_1(N_1 N_2 - N_5 N_6)^2 X_2}{N_3(N_1 - N_5)(N_2 - N_6) X_\gamma}$$

| Method | Activity (Bq) |
|---|---|
| Coincidence with HPGe detectors | 298.4±6.5 |
| Coincidence with NaI detectors | 300.0± 1.3 |

# $^{125}$I HPGe-HPGe

- $\varepsilon_1^{X,p} = z_1\,\varepsilon_1^{\gamma,p}$ - Monte Carlo (MC) simulation
- EGSnrc with decay generator
- Efficiency calibration in low-energy range



# Conclusions and perspectives

- Simple and interesting education tool
- Easy to reach <5% deviation

- Corrections needed to achieve good accuracy (deadtime, angular correlation ...)
- Works only for point sources (sometimes complicated point source production)

  Extension to volume sources possible (Vidmar, T et al. Appl. Radiat. Isot. 67, 160–163)

Try it!

# Experimental facilities

Nutech Coincidence Low Energy Germanium Sandwich Spectrometer (NUCLeGeS) - two HPGe detectors

Dual NaI(Tl) system

# Digital acquisition systems


DT5780 front view

- CAEN MCA (DT5780 and N6781)

2 x 100 MS/s 14 bit ADC

10 ns time stamp resolution

- MC²Analyzer Control Software

graphical interface

for DPP/PHA

# List mode spectrum acquisition

- Each event is recorded with its energy and timestamp (when it hit the detector)
- In our case timestamp is time in units of 10 ns

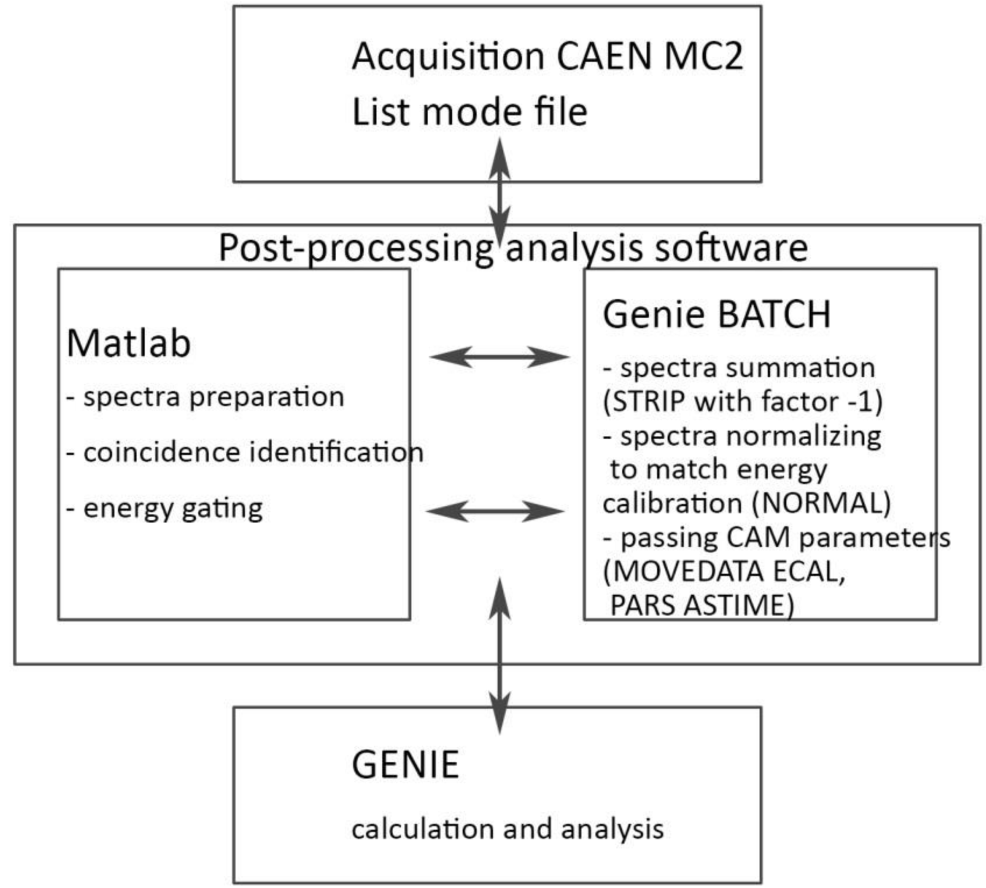
| Timestamp | Energy |
|---|---|
| 29469567 | 7188 |
| 29631038 | 166 |
| 39847353 | 1029 |
| 40560649 | 6986 |
| 42757345 | 1438 |
| 43354128 | 4594 |
| 45868475 | 1265 |
| 46434394 | 522 |
| 46765219 | 3148 |
| 47342918 | 1272 |
| 48050647 | 202 |
| 49174601 | 1097 |
| 49342539 | 183 |
| 50014278 | 387 |

Normal spectrum
- long exposure
photograph

List mode spectrum
- video

# Analysis software

- Acquisition controlled by CAEN MC²Analyzer Control Software
- Data recorded in a list mode file
- Data analysis performed in post-processing using MATLAB based software that creates two energy spectra out of list mode files
- Coincidence spectra identified based on the selected coincidence resolving time and optional energy gating
- All the spectra are saved in .TKA format and then converted to GENIE 2000 .CAM
- Spectrum analysis (peak search, calibrations, activity calculation …) done using GENIE 2000 software



# Analysis software

- GUI
- easy to change between different detector systems
- Produces Genie .CAM file with all parameters needed (live time, real time, acquisition start date … )