



Gamma-ray spectrometry of radionuclides with cascading gamma-rays

J. Gasparro, M. Hult, P.N. Johnston, H. Tagziria

*Institute for Reference Materials and Measurements (IRMM)
Geel, Belgium*

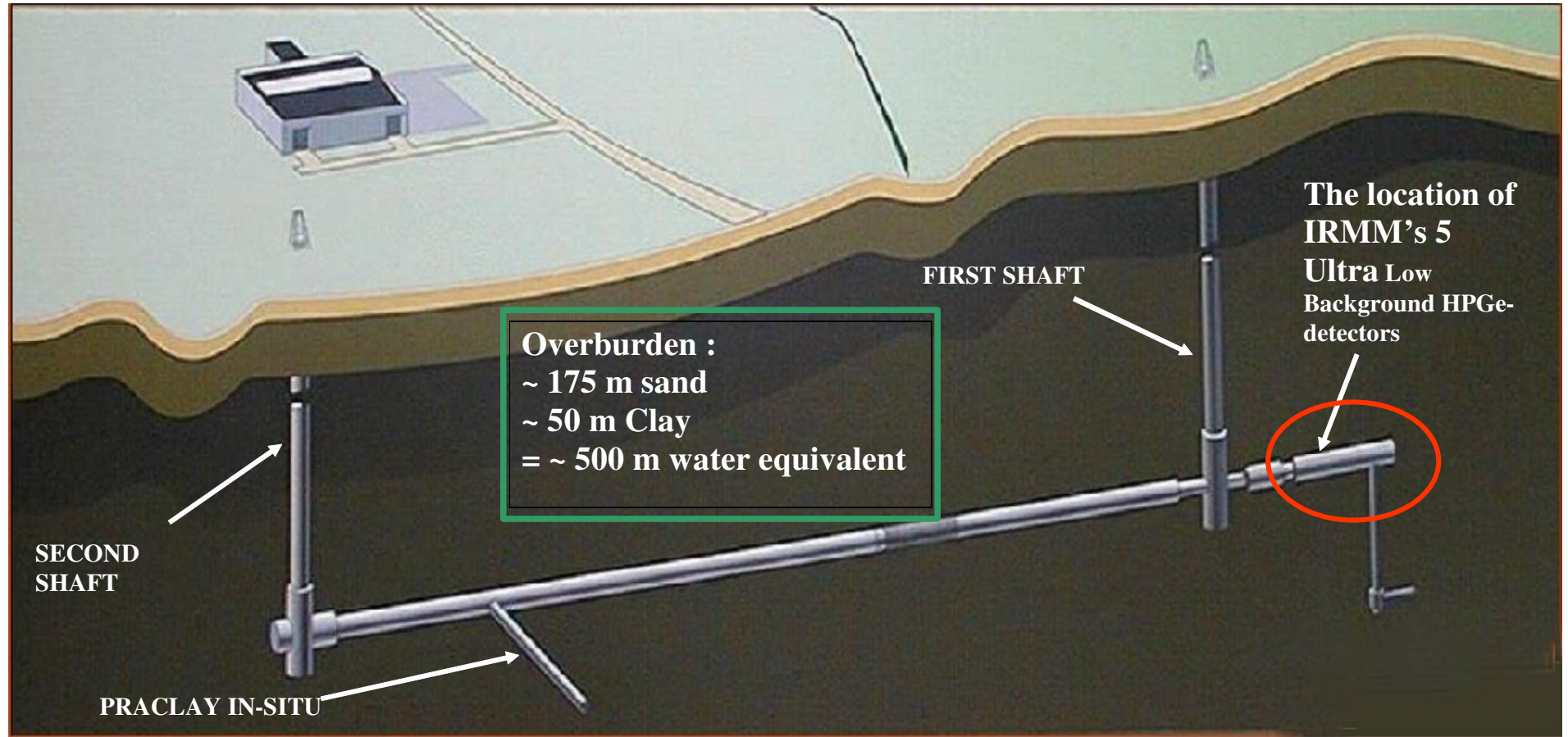
<http://www.irmm.jrc.be>
<http://www.jrc.cec.eu.int>





Schematic view of HADES

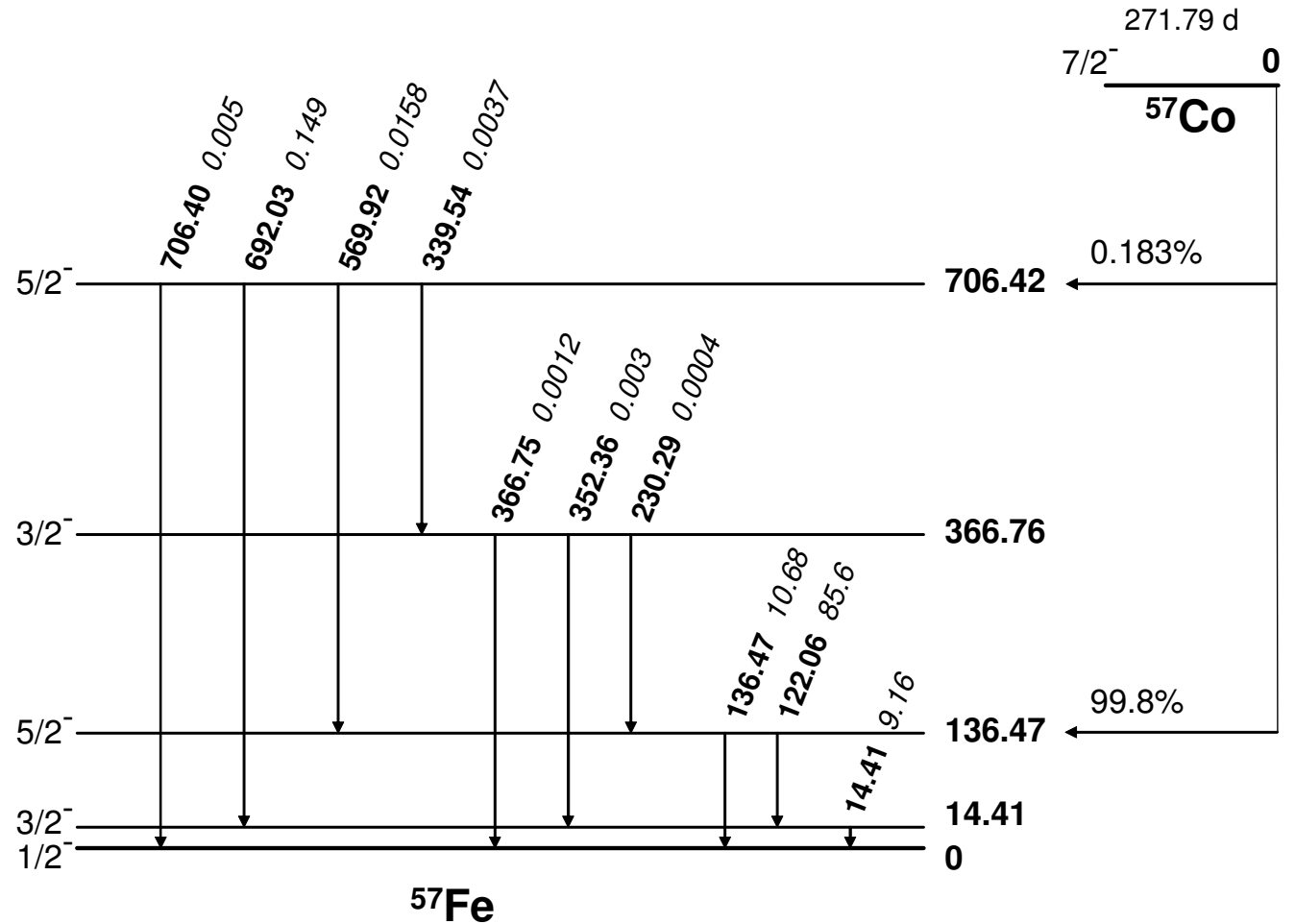
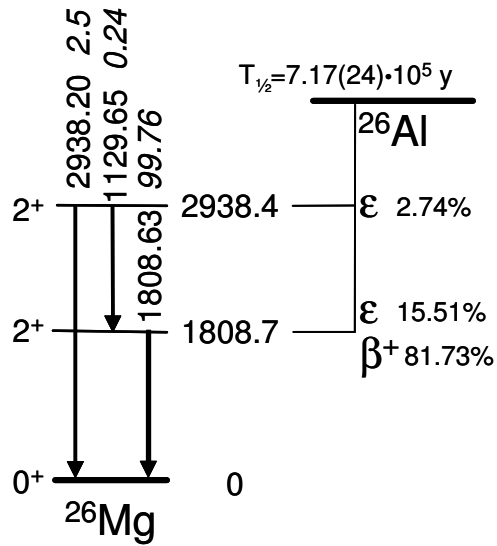
IRMM operates HPGe-detectors in the underground laboratory HADES, located at SCK·CEN





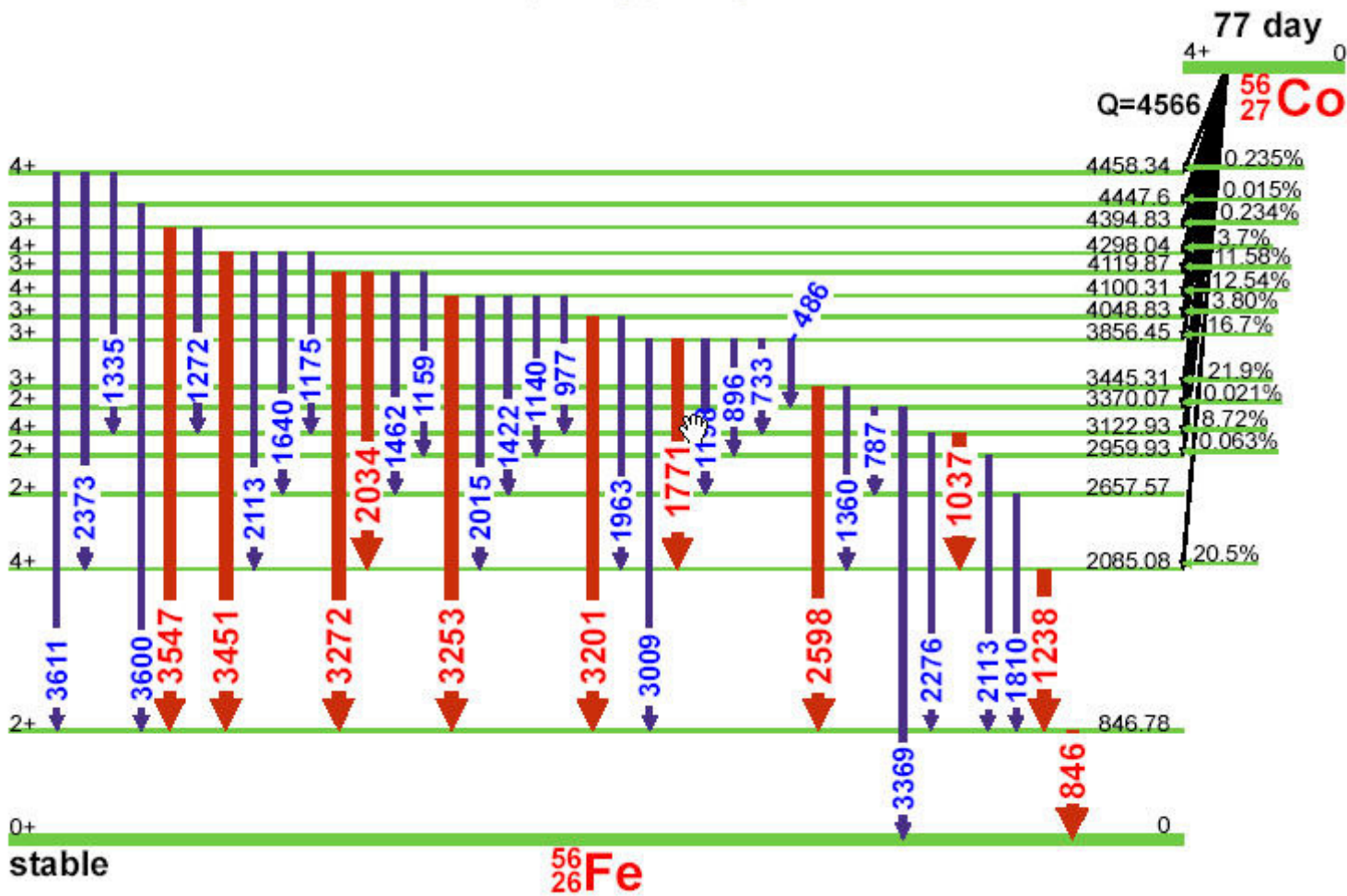


Examples of decay schemes

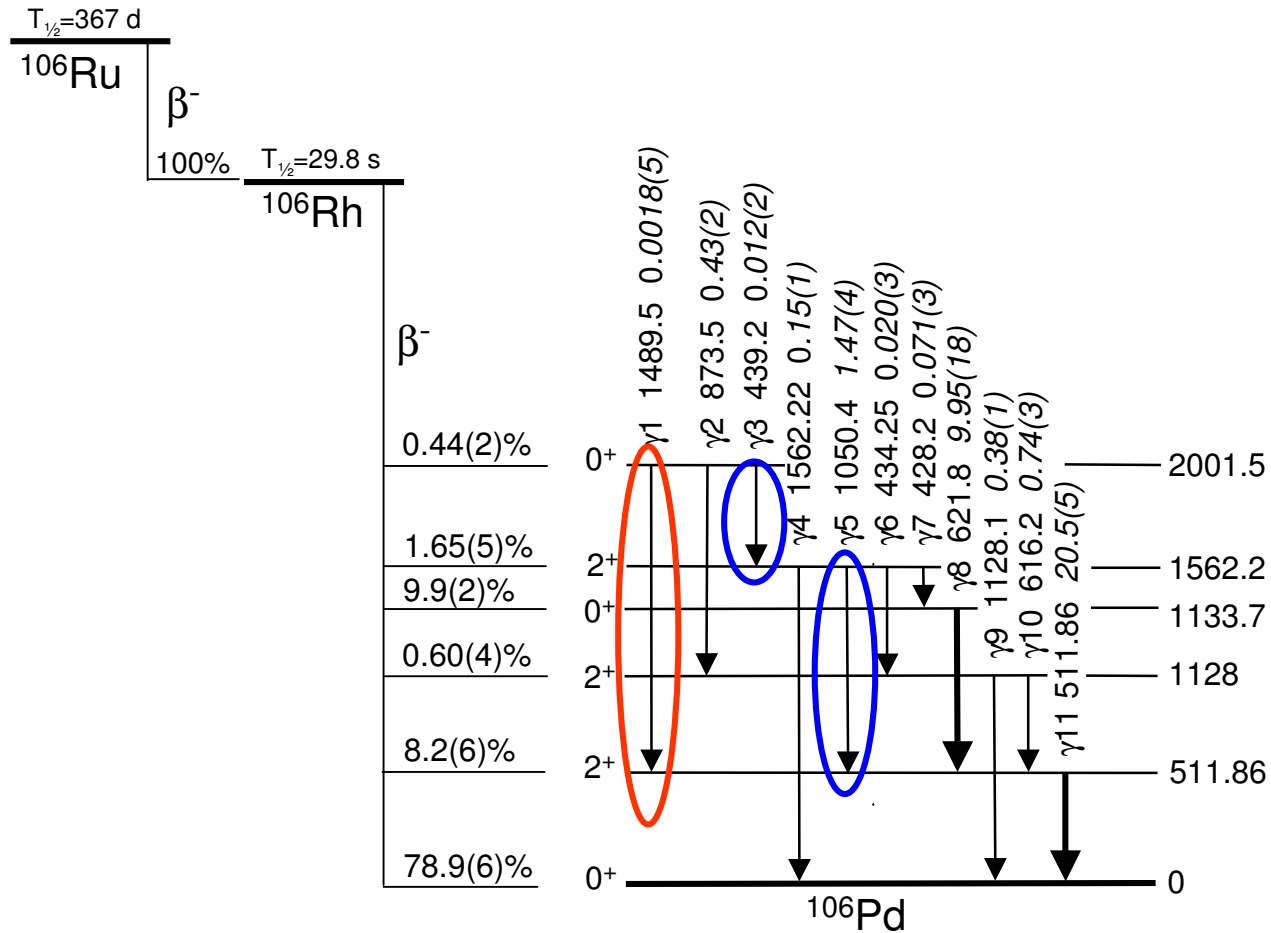




^{56}Co decay scheme (simplified)

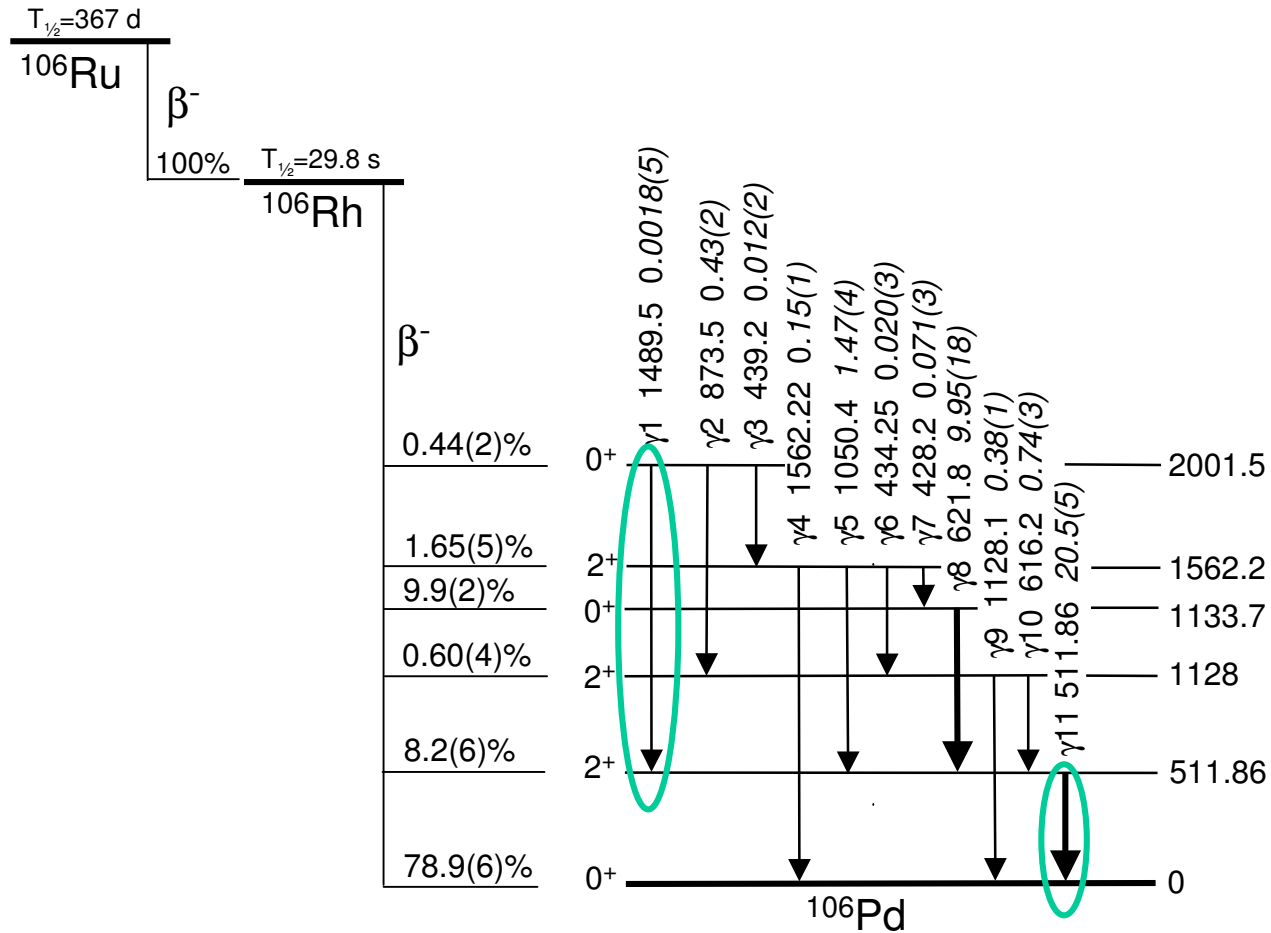


^{106}Ru decay scheme (simplified)



Summing in

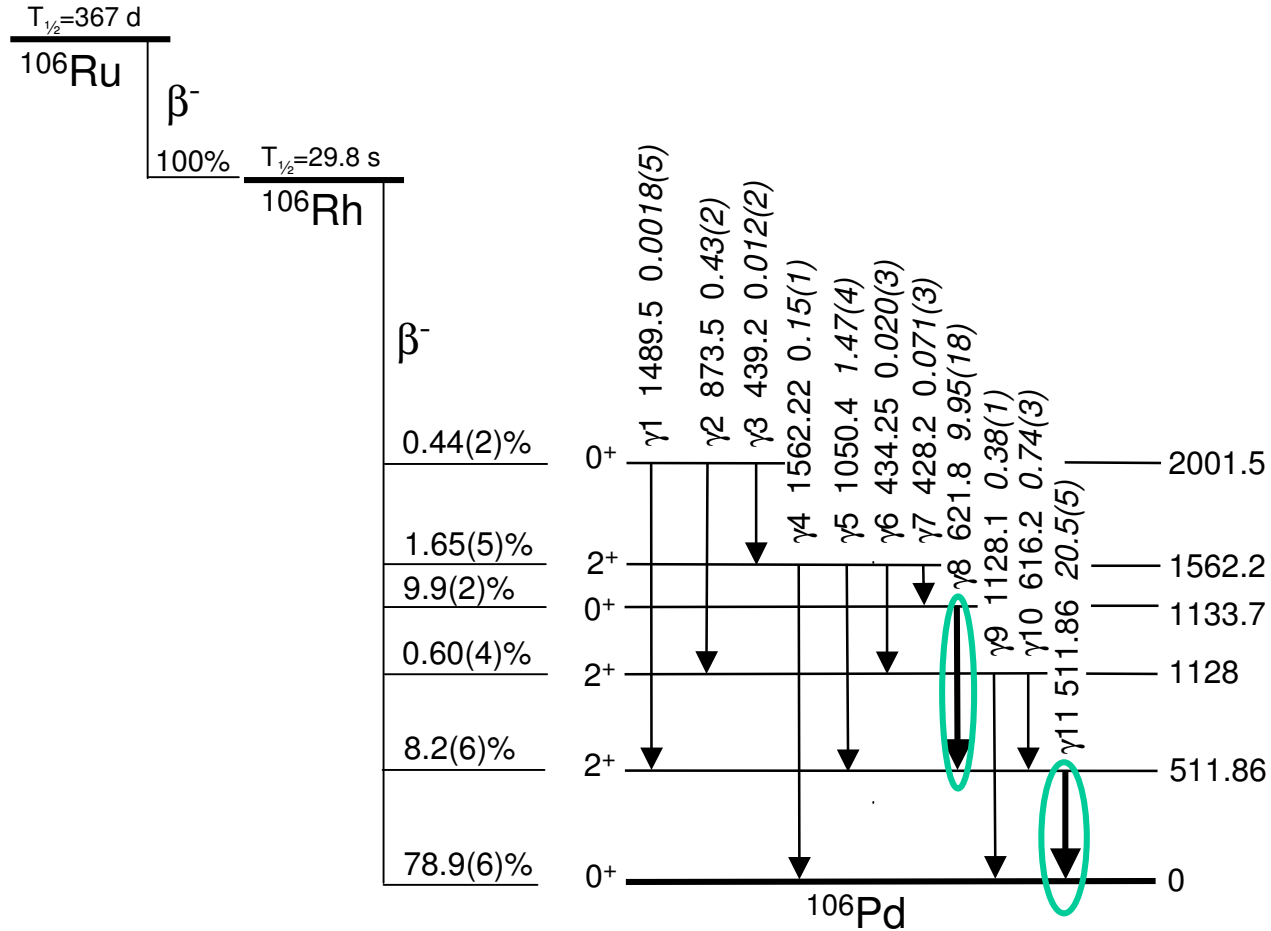
^{106}Ru decay scheme (simplified)



Summing out



^{106}Ru decay scheme (simplified)

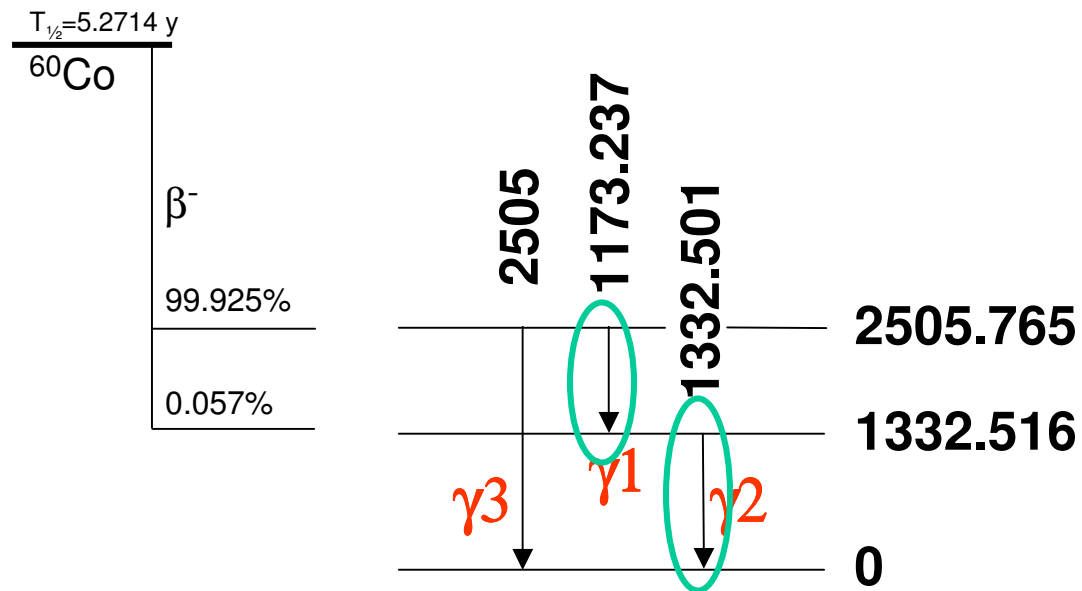


Summing out





^{60}Co decay scheme

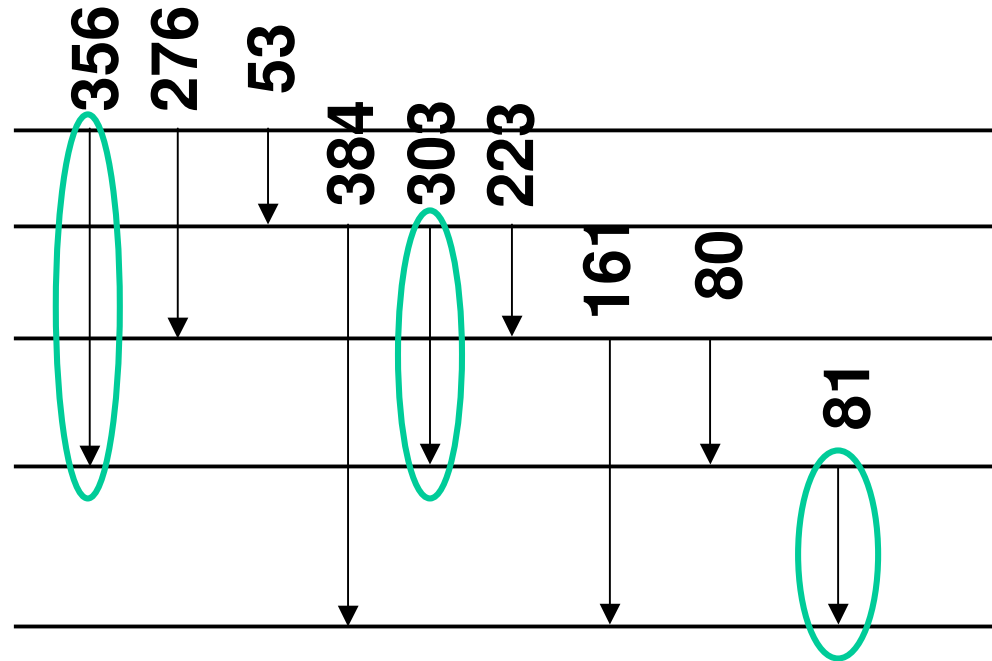


Summing out





^{133}Ba decay scheme



Summing out



Different methods

- **No corrections**
- **Use standard of the same radionuclide with the same geometry**
- **Use tables of correction factors**
- **Calculate correction factors using FEP efficiencies and total efficiencies**
- **Calculate absolute efficiencies per decay using Monte Carlo method**



No summing correction

50% planar detector

Water in TEFLON container

height: 4 cm
diameter: 5 cm

Point source

For ^{106}Ru	622 keV	20%	45%
For ^{60}Co	1174 keV	14%	31%
For ^{133}Ba	356 keV	15%	32%
	304 keV	23%	52%
	82 keV	30%	61%



No summing correction

Advantages

It 's fast and easy

Drawback

Gives incorrect results (at least for close geometry)



Different methods

- No corrections
- **Use standard of the same radionuclide with the same geometry**
- **Use tables of correction factors**
- **Calculate correction factors using FEP efficiencies and total efficiencies**
- **Calculate absolute efficiencies per decay using Monte Carlo method**



Standard of same radionuclide with same geometry

Advantages

Gives correct results while doing no corrections for coincidence summing

Drawback

It is necessary to have one standard for each radionuclide measured



Different methods

- No corrections
- Use standard of the same radionuclide with the same geometry
- **Use tables of correction factors**
- **Calculate correction factors using FEP efficiencies and total efficiencies**
- **Calculate absolute efficiencies per decay using Monte Carlo method**

Tables of correction factors

Correction factors for point sources directly on endcap

		GeLi 12.5% point source	coaxial 25% point source	planar 50% point source	ratio 50% / 12.5%	ratio 50% / 25%
	Energy (keV)					
Ba-133	81	1.30	1.68	1.61	1.24	0.96
	303	1.16	2.05	1.53	1.32	0.74
	356	1.13	1.69	1.32	1.17	0.78
Co-60	1173	1.16	1.17	1.31	1.13	1.12
	1332	1.17	1.18	1.33	1.14	1.13



Tables of correction factors

Correction factors for volume sources

		GeLi 30%		GeLi 12%	planar 50%	Ratio 78cm ³ / 14 cm ³	Ratio 78cm ³ / 33 cm ³	Ratio 78cm ³ / 1000 cm ³
Volume (cm ³)		14	33	1000	78			
	Energy (keV)							
Ba-133	81	1.21	1.14	1.054	1.30	1.07	1.14	1.23
	303	1.08	1.05	1.015	1.23	1.14	1.17	1.21
	356	1.07	1.04	1.012	1.15	1.07	1.11	1.14
Co-60	1173	1.14	1.09	1.033	1.14	1.00	1.05	1.10
	1332	1.13	1.1	1.034	1.15	1.02	1.05	1.11



Tables of correction factors

Advantages

If detector and geometry similar to the ones in Tables,
it is **FAST, EASY** and **GIVES CORRECT RESULTS**

Drawback

Otherwise, it is not easy to correct for different
detectors and geometry



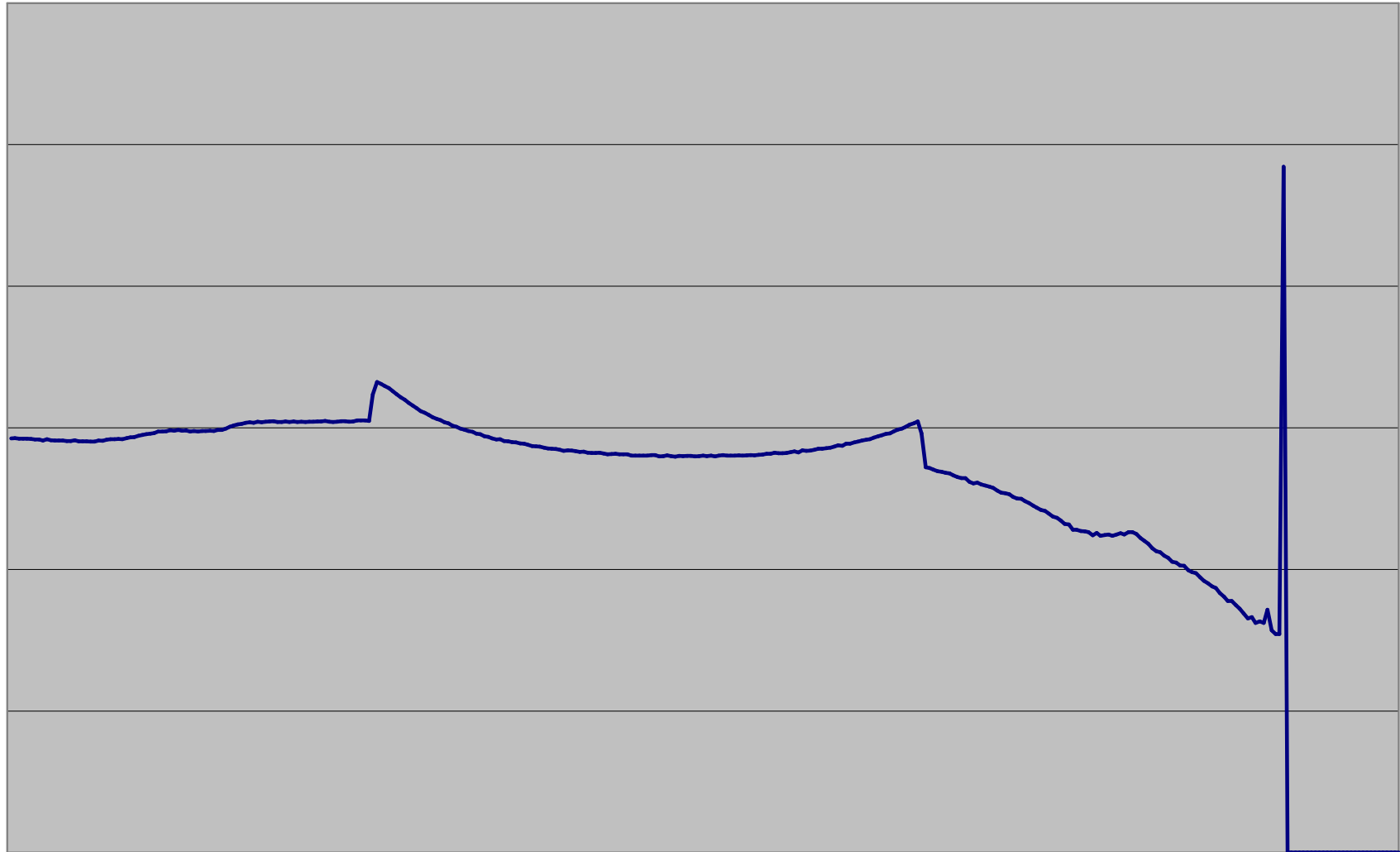
Different methods

- No corrections
- Use standard of the same radionuclide with the same geometry
- Use tables of correction factors
- **Calculate correction factors using FEP efficiencies and total efficiencies**
- **Calculate absolute efficiencies per decay using Monte Carlo method**



Total efficiency and FEP efficiency

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Analytical method

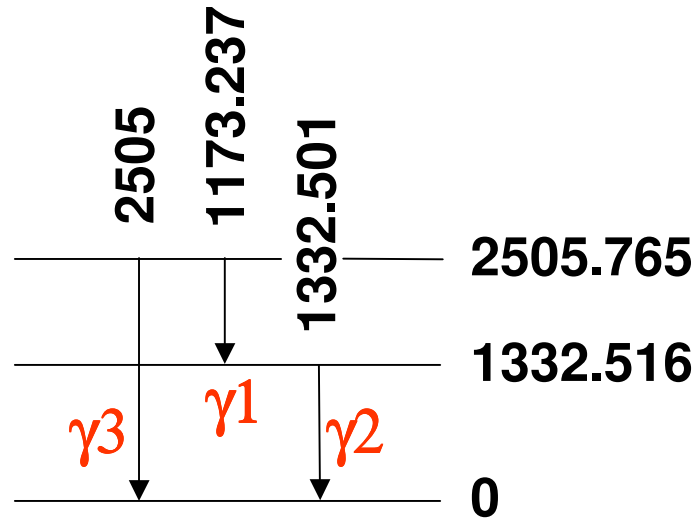
$T_{1/2} = 5.2714 \text{ y}$

^{60}Co

β^-

99.925%

0.057%



$$\epsilon_{d1} = p_1 \epsilon_1 (1 - \epsilon_{t2})$$

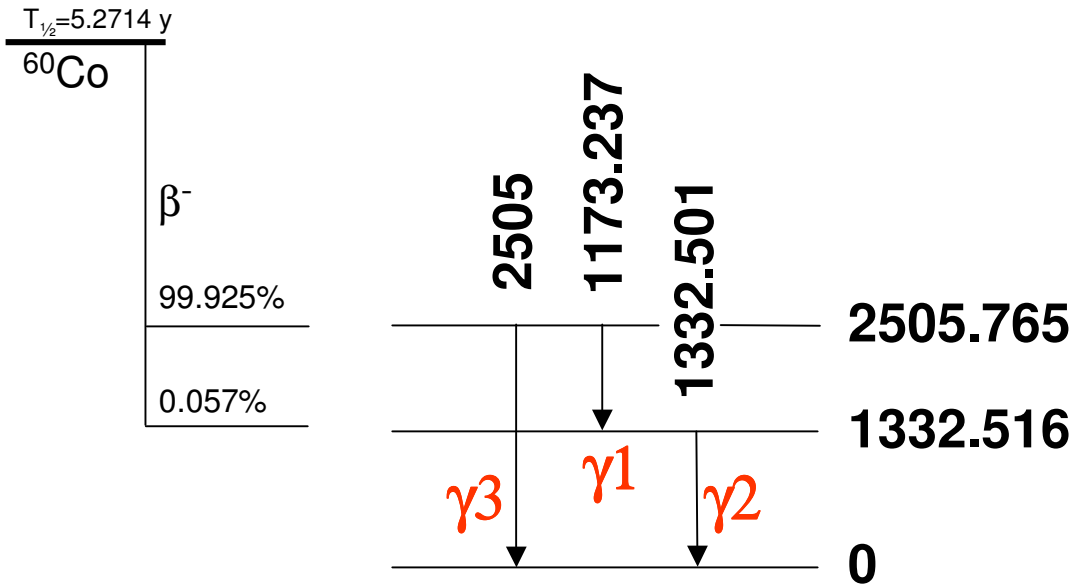
$$\epsilon_{d2} = p_2 \epsilon_2 [1 - (p_1/p_2) \epsilon_{t1}]$$

$$\epsilon_{d3} = p_3 \epsilon_3 + p_1 \epsilon_1 \epsilon_2$$

For a point source

	FEP ϵ (no correction)	FEP ϵ (with correction)	FEP ϵ (with coincidence summing)	Relative difference (%)
1173 keV	0.0413	0.03159	0.03158	0.05
1332 keV	0.0371	0.0280	0.0279	0.20

Analytical method



$$\epsilon_{d1} = p_1 \epsilon_1 (1 - \epsilon_{t2})$$

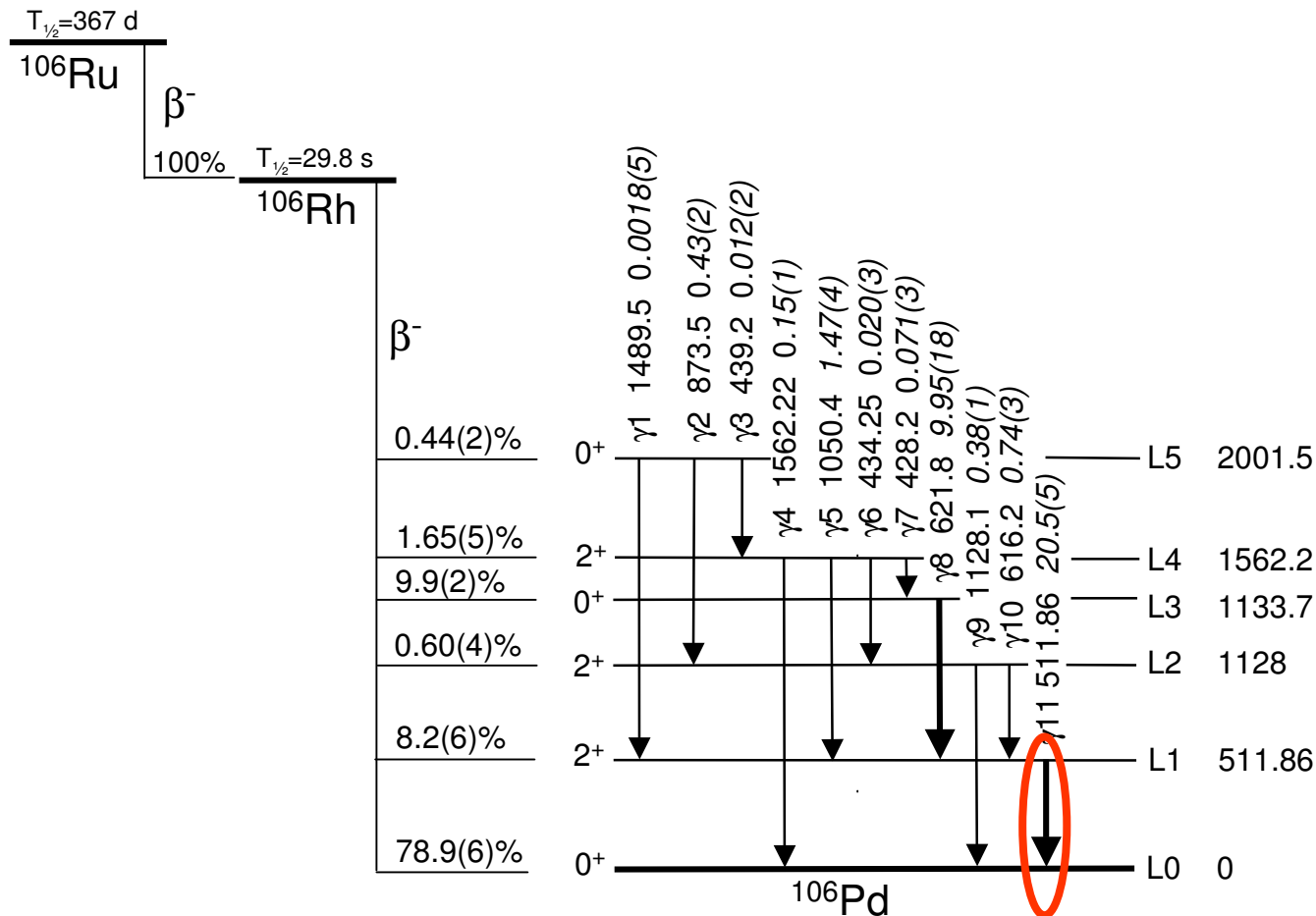
$$\epsilon_{d2} = p_2 \epsilon_2 [1 - (p_1/p_2) \epsilon_{t1}]$$

$$\epsilon_{d3} = p_3 \epsilon_3 + p_1 \epsilon_1 \epsilon_2$$

For a volume source

	FEP ϵ (no correction)	FEP ϵ (with correction)	FEP ϵ (with coincidence summing)	Relative difference (%)
1173 keV	0.0164	0.0145	0.0144	0.72
1332 keV	0.0148	0.0130	0.0128	1.22

Analytical method



$$\epsilon_{d11} = p_{11}\epsilon_{11} - \epsilon_{11}[p_1\epsilon_{t1} + p_2\epsilon_{t2}f_{10} + p_3\epsilon_{t3}(f_5 + f_6f_{10} + f_7) + p_5\epsilon_{t5} + p_6\epsilon_{t6}f_{10} + p_7\epsilon_{t7} + p_8\epsilon_{t8} + p_{10}\epsilon_{t10}]$$



Analytical method

Advantages

For radionuclide with simple decay schemes, it is easy to calculate and gives accurate results

Drawback

Intractable for radionuclides with complex decay schemes, with different types of interactions



Different methods

- No corrections
- Use standard of the same radionuclide with the same geometry
- Use tables of correction factors
- Calculate correction factors using FEP efficiencies and total efficiencies
- **Calculate absolute efficiencies per decay using Monte Carlo method**



Monte Carlo radiation transport method

Definition

Random paths of individual particles are simulated

by using random numbers

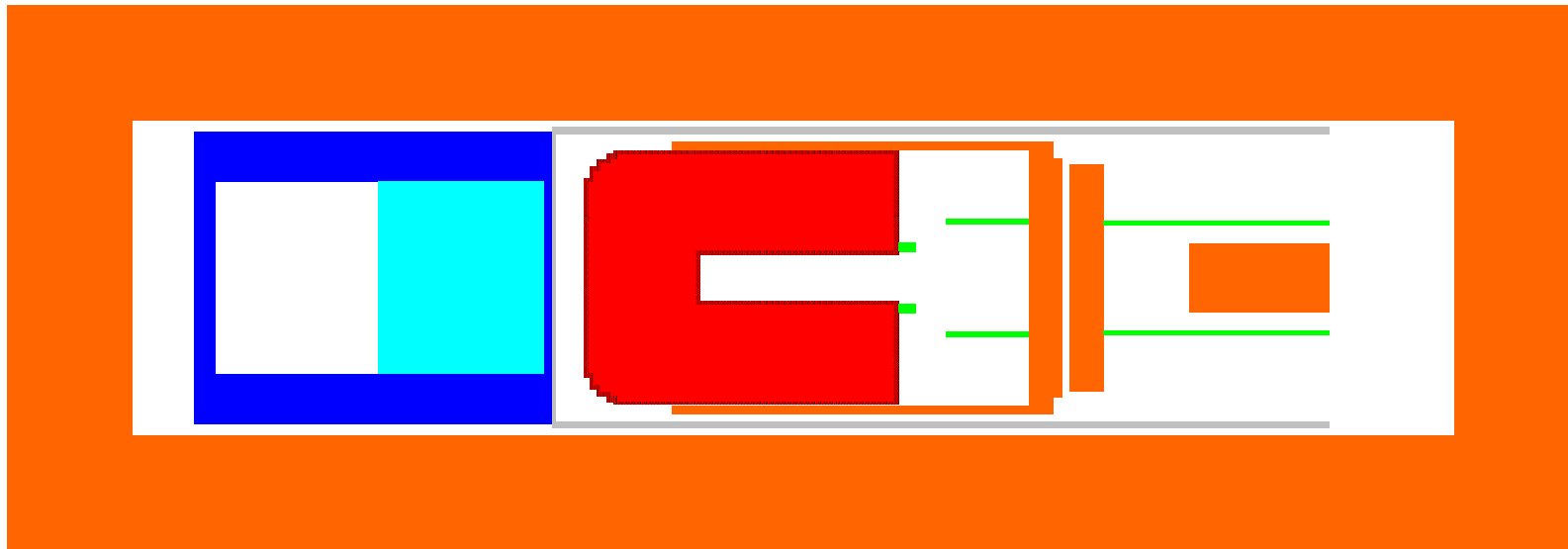
to sample from probability distributions governing the physical processes involved










Monte Carlo method

It is a numerical method based on simulation!

- Each photon tracked along its path



	Source Material
	LDPE
	Teflon
	Window - Al
	Ge
	Ge deadlayer
	Cu



Monte Carlo method

It is a numerical method based on simulation!

- **Each photon tracked along its path**
- **All photon interactions are included and secondary particles are also tracked**
- **Energy deposited in Ge is computed for a large number of photons**



Estimate of the response function

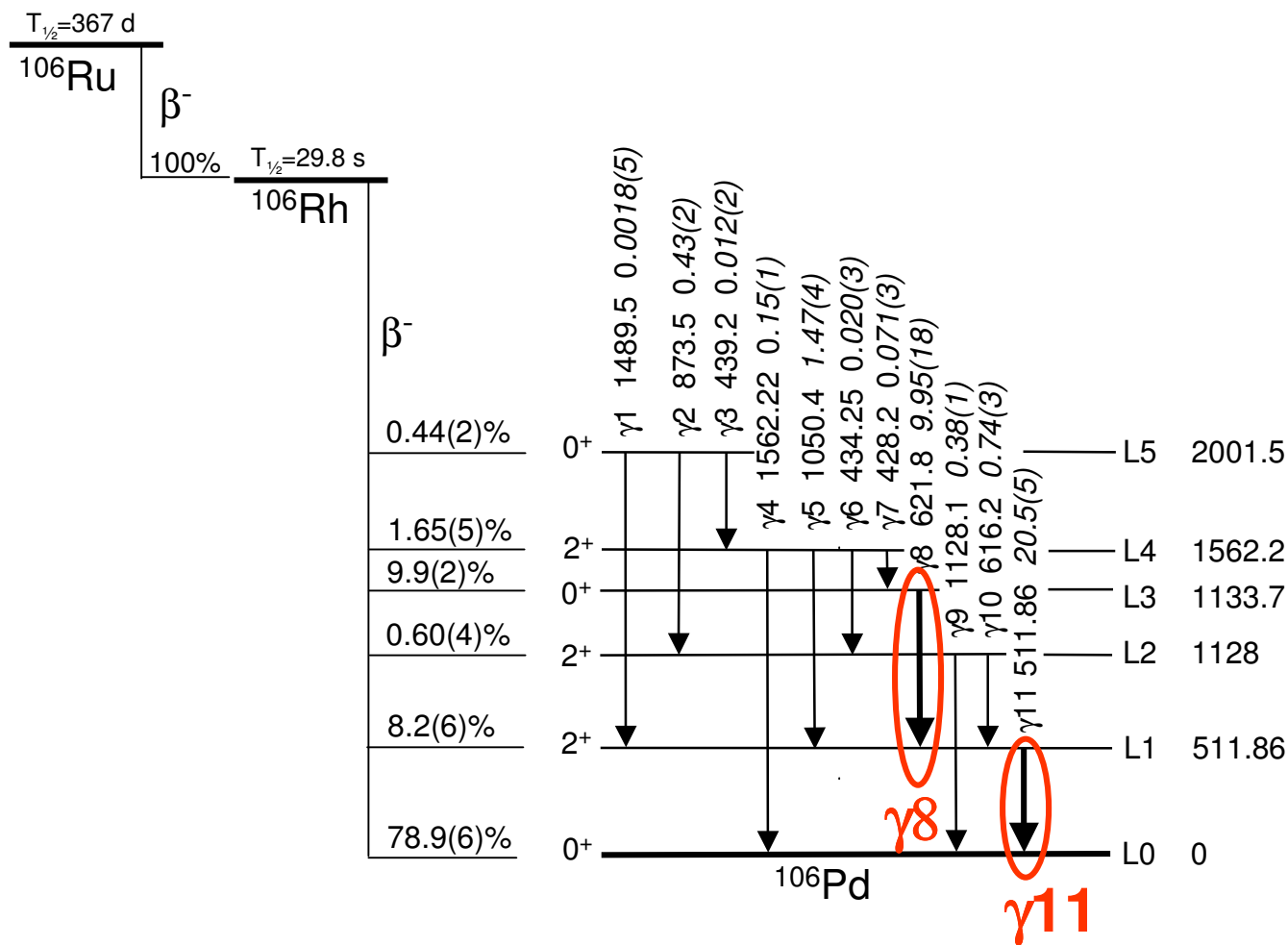


Response function

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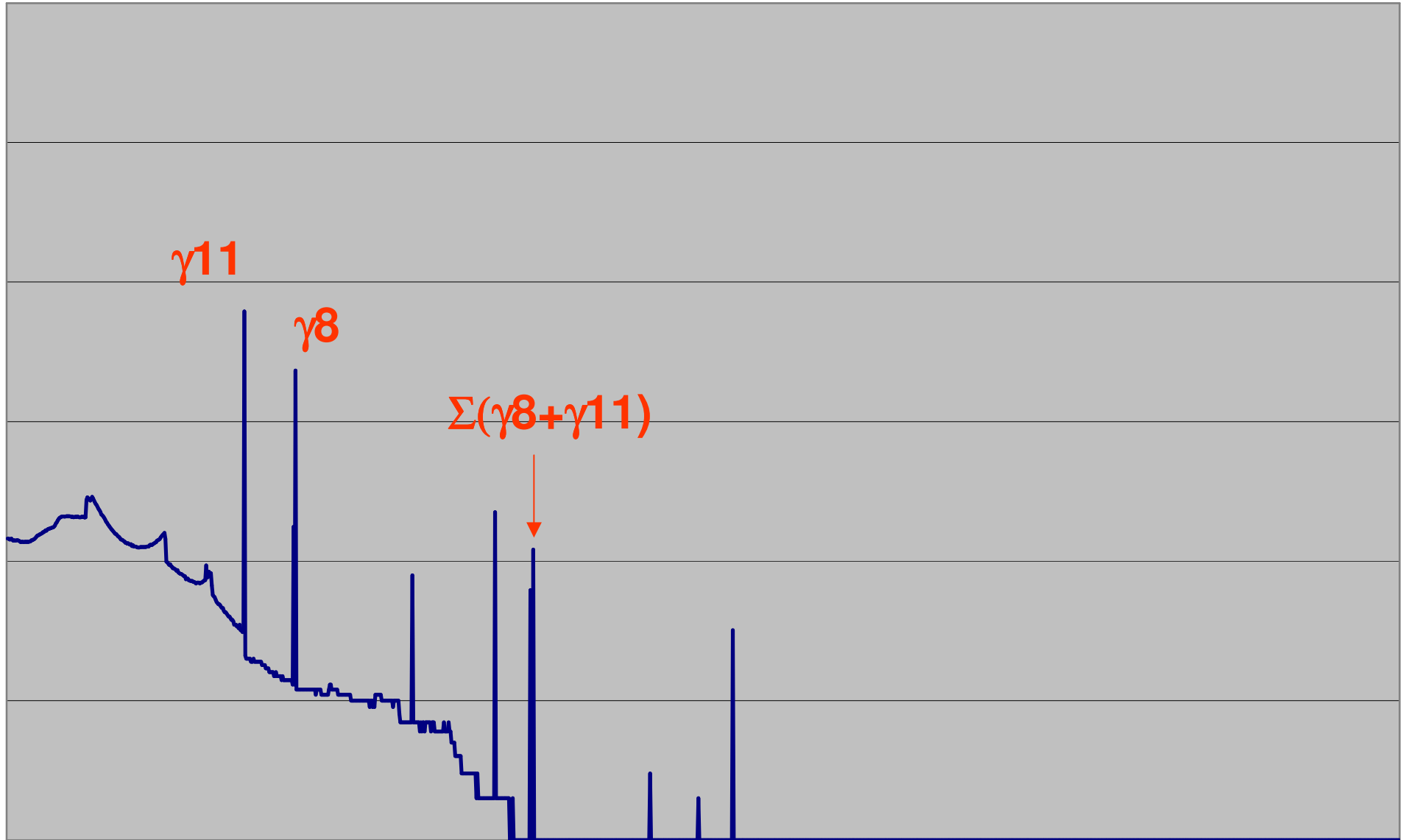
Simplified decay scheme of ^{106}Rh





Response function for ^{106}Rh

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Main Monte Carlo radiation transport codes

Code	Pros	Cons	Main use / user
EGS 4	Best electron transport	-Somewhat complex to use	Dose planning / hospital
EGSnrc		-Bad geometry visualisation	
PENELOPE		-No neutrons	
GESPECOR	-User friendly -Specially for γ -spec	-No neutrons -Not freeware	Gamma-spec
GEANT 4	-Very versatile -Many different particles	Complex to use	High energy physics
MCNP5	State-of-the-art for neutrons	No freeware for summing	Neutron physics

**No
expensive
course
to follow**

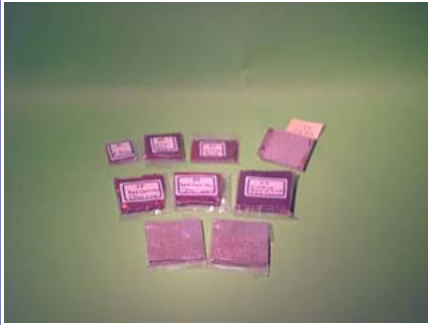
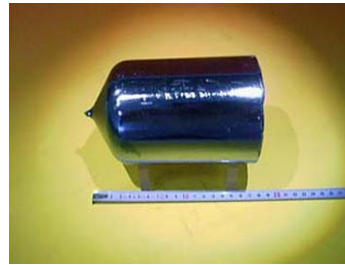


Main Monte Carlo radiation transport codes

Code	Platform	Web site
EGS 4	VAX, DOS (PC), UNIX	Mails to: http://www.slac.stanford.edu/egs/egslist.html Home page: EGS4 http://www.slac.stanford.edu/egs/ Distribution: EGS4.3 http://www.irs.inms.nrc.ca/inms/irs/EGS4/get_egs4.htm Specifications: http://www.nea.fr/abs/html/ccc-0331.html
EGSnrc	UNIX, PC LINUX	EGSnrc http://www.irs.inms.nrc.ca/V3_EGSnrc/EGSnrc.html EGSnrcMP http://www.irs.inms.nrc.ca/inms/irs/EGSnrc/EGSnrc.html
PENELOPE	UNIX, PC LINUX, PC Windows	Mails to: http://www.nea.fr/listsmh/penelope/maillist.html Specifications: http://www.nea.fr/abs/html/nea-1525.html
GESPECOR	PC Windows	www.matec-online.de
GEANT 4	UNIX, PC LINUX, PC Windows	http://wwwasd.web.cern.ch/wwwasd/geant/ http://geant4.web.cern.ch/geant4/
MCNP5	UNIX, PC LINUX, PC Windows	Mails to: http://laws.lanl.gov/x5/MCNP/forum.html Home page: http://mcnp-green.lanl.gov/index.html Specifications: http://www.nea.fr/abs/html/ccc-0701.html



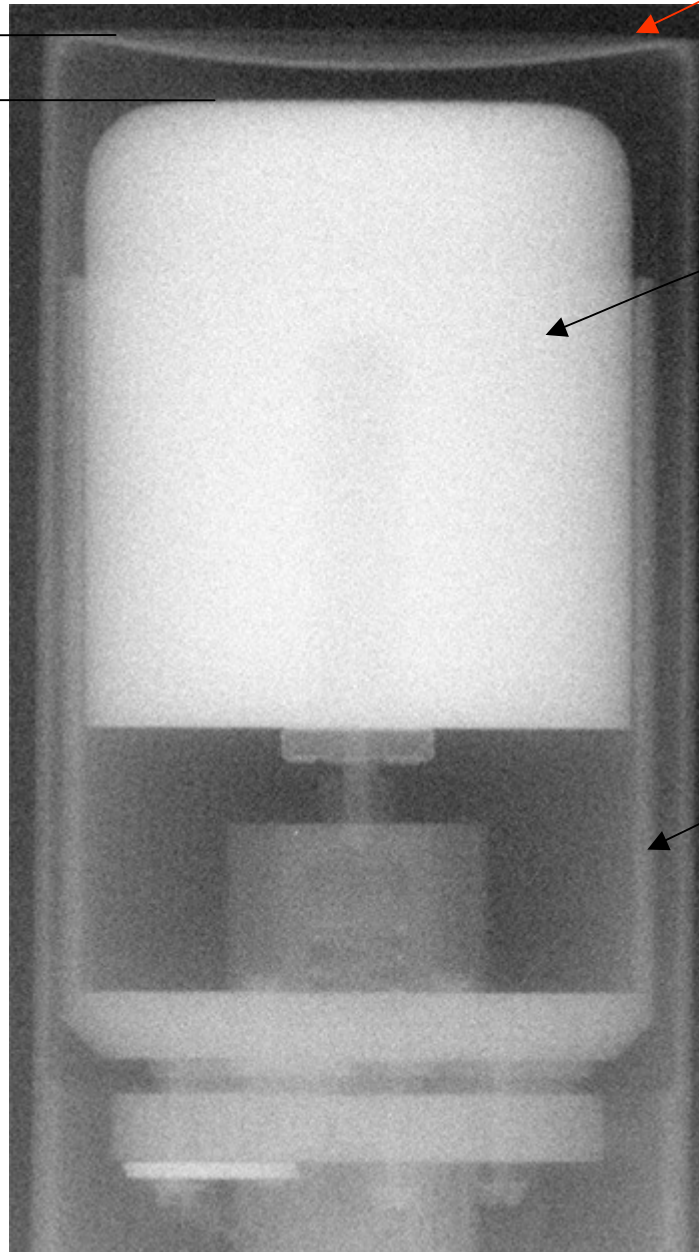
Some samples measured at IRMM





Radiography of a coaxial detector

Distance
crystal to
window



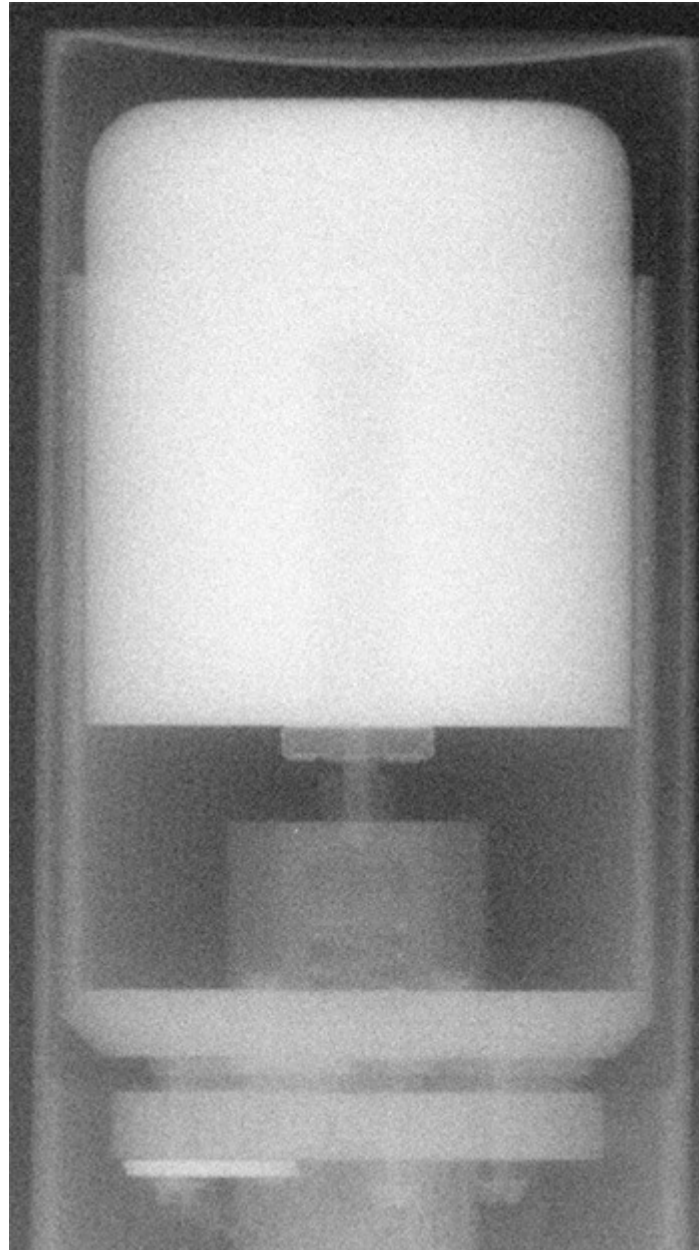
Window

Germanium
crystal

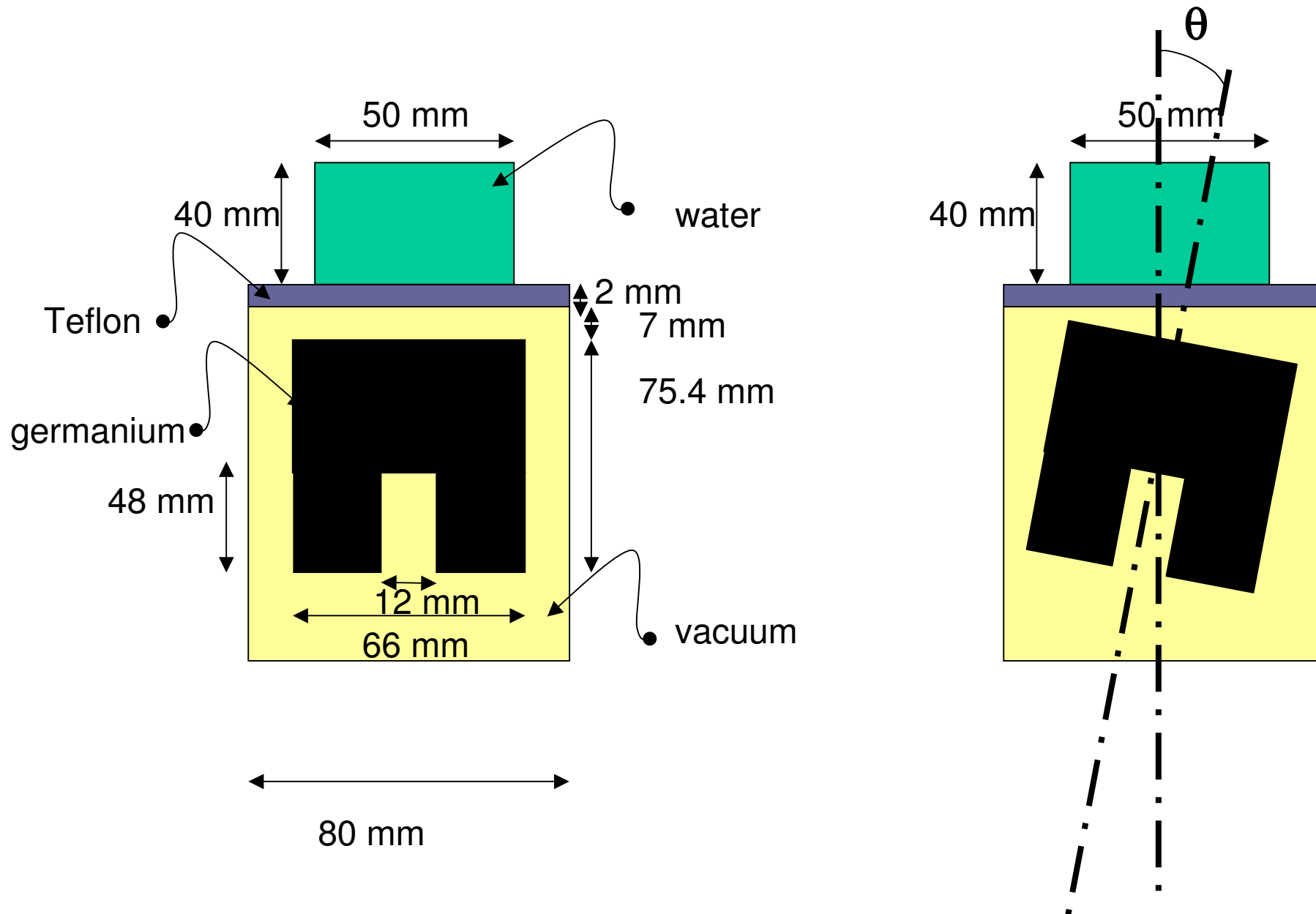
Crystal holder



Radiography of a coaxial detector

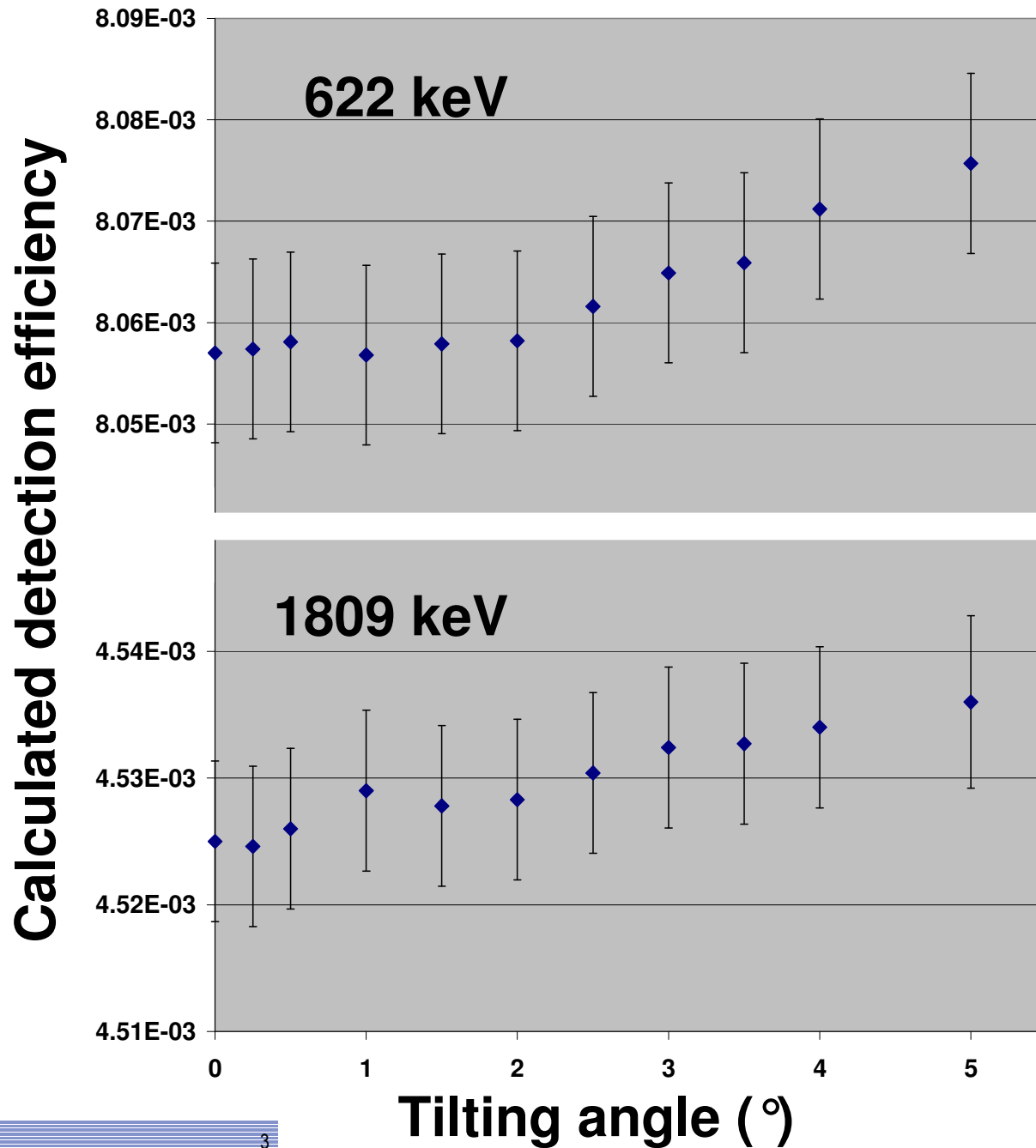


Effect of tilting the crystal



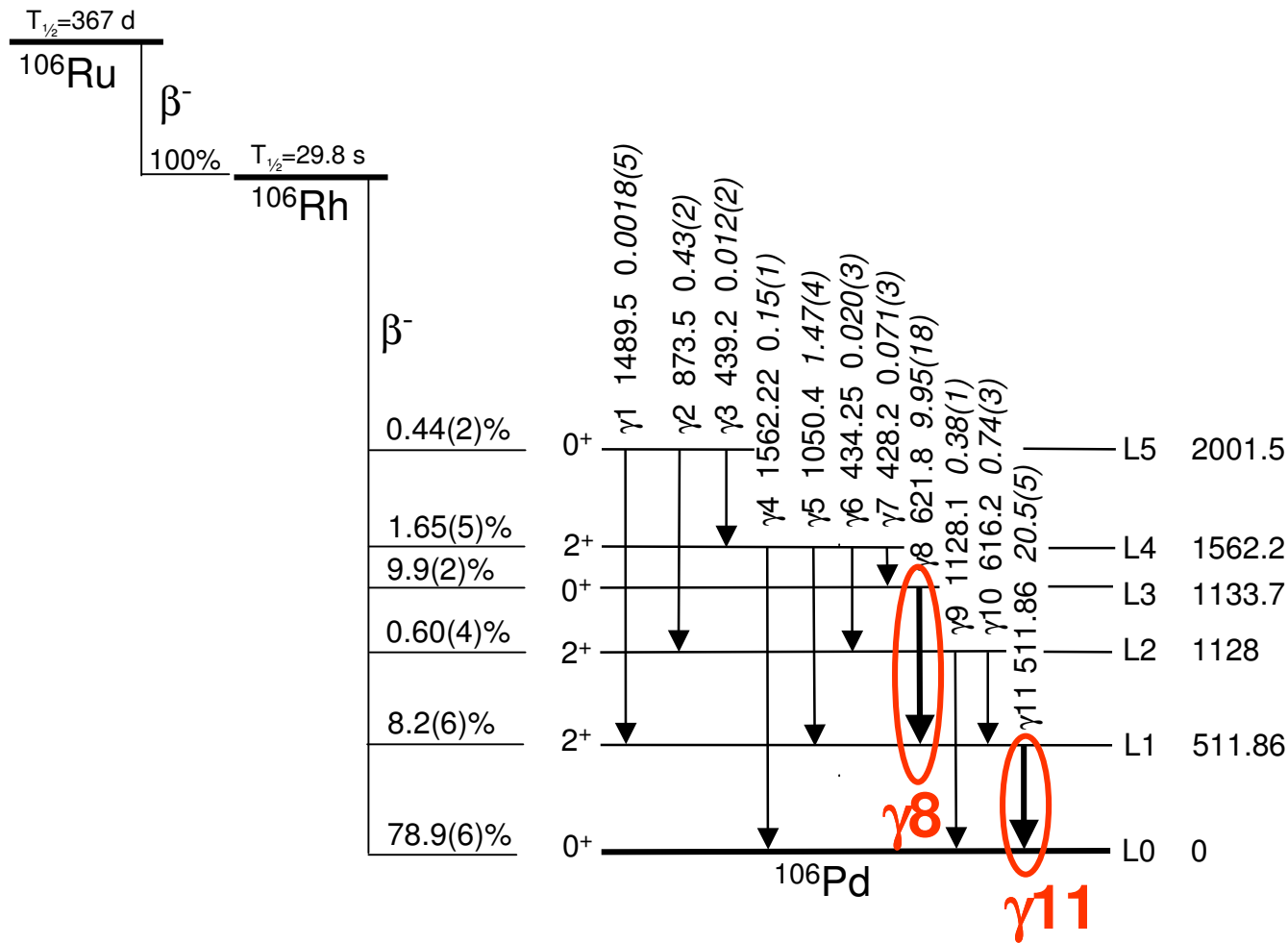


Efficiency from Monte-Carlo simulation



**No significant difference
between efficiencies at
0° and 5°**

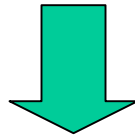
Simplified decay scheme of ^{106}Rh





Effect of modelling rounded edges

If rounded edges not included



Efficiencies overestimated by

γ_{11}		6.4%	$\pm 0.3\%$
γ_8		5.2%	$\pm 0.6\%$
$\Sigma(\gamma_8 + \gamma_{11})$		14 %	$\pm 3 \%$



Other geometrical parameters influencing the efficiency

Variation of efficiency (%)

Parameter	γ_{11}		γ_8	
	Deadlayer thickness			
Front	1.3	(3)	1.2	(6)
Side	0.8	(3)	0.9	(6)
Back	1.0	(3)	1.0	(6)
Crystal to window	1.6	(3)	1.3	(6)
No shield	1.4	(3)	2.4	(6)



Accuracy of the code

Uncertainty of the physical cross section data

For photons

3-5% for photoelectric effect

2-3% for Compton interaction (<1% for light elements)

5% for pair production

For electrons and positrons (<100keV)

2-3% for low Z-materials

5-10% for high Z-materials

For electrons and positrons (>100keV)

1-2%

$$\mathcal{E} = \mathcal{E}_{sample}^{MC} \frac{\mathcal{E}_{std}^{meas}}{\mathcal{E}_{std}^{MC}}$$



Monte Carlo method

Advantages

Gives directly efficiency per decay with all the corrections taken into account (coincidence summing, self-attenuation...)

Reasonable accuracy

Drawback

Most MC Softwares are not user-friendly

Long calibration and model elaboration needed



Comparison of nuclear decay data sets collected from different databases

Relative variation of efficiency compared to ENSDF

	γ_{11}		γ_8		$\Sigma(\gamma_8+\gamma_{11})$	
Nucleide	0.57	(23)	0.6	(5)	0.0	(24)
Radiochemical Manual	3.96	(24)	3.4	(6)	3.3	(24)

- Different databases give different values



Conclusions





The most adequate method for cascading gamma-rays is the:



method

Conclusions

The « best method » depends on what you want to do:

Routine measurements		Standard with same geometry
Samples with different geometries		Monte Carlo method
Low activity samples		Most practical method
Qualitative analysis		No correction or Table of correction factors



Thank you for your attention







Random number generator

1 M histories

300 M histories

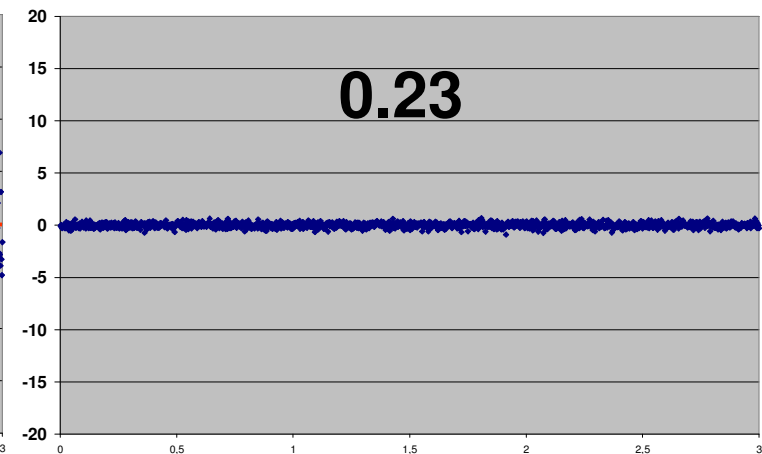
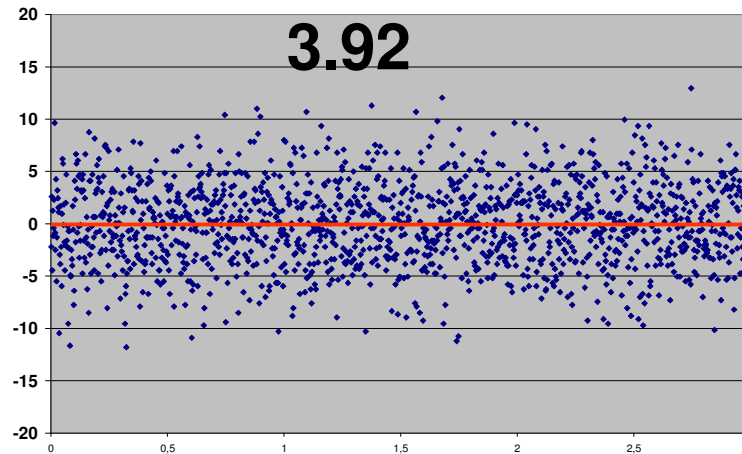
Expected
rel std dev
(%)

3.87

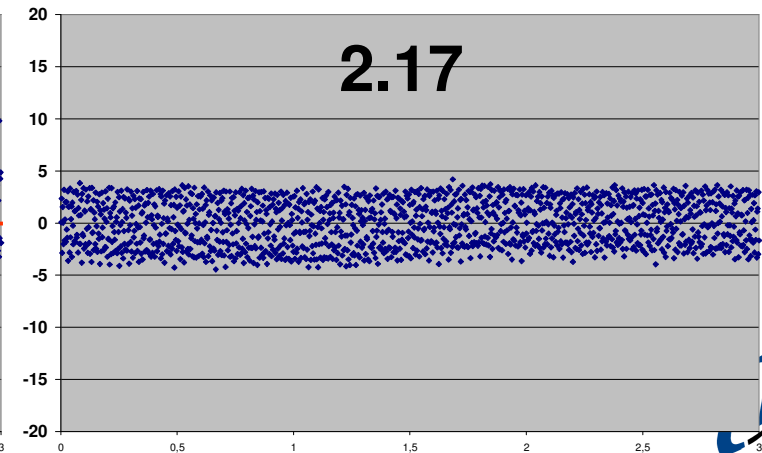
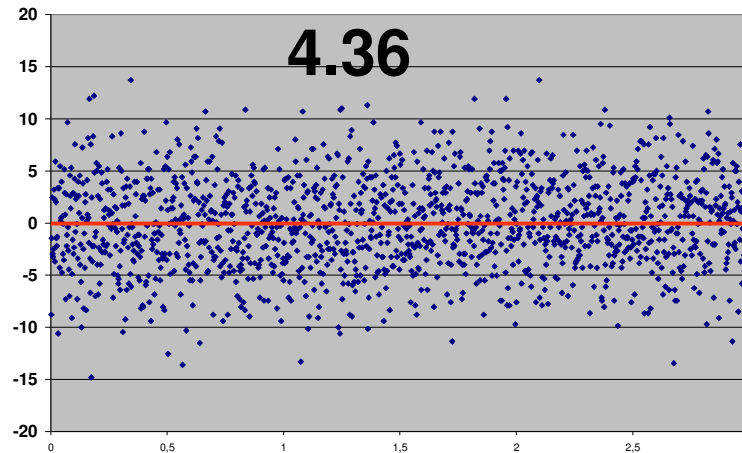
0.22

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RNG 1

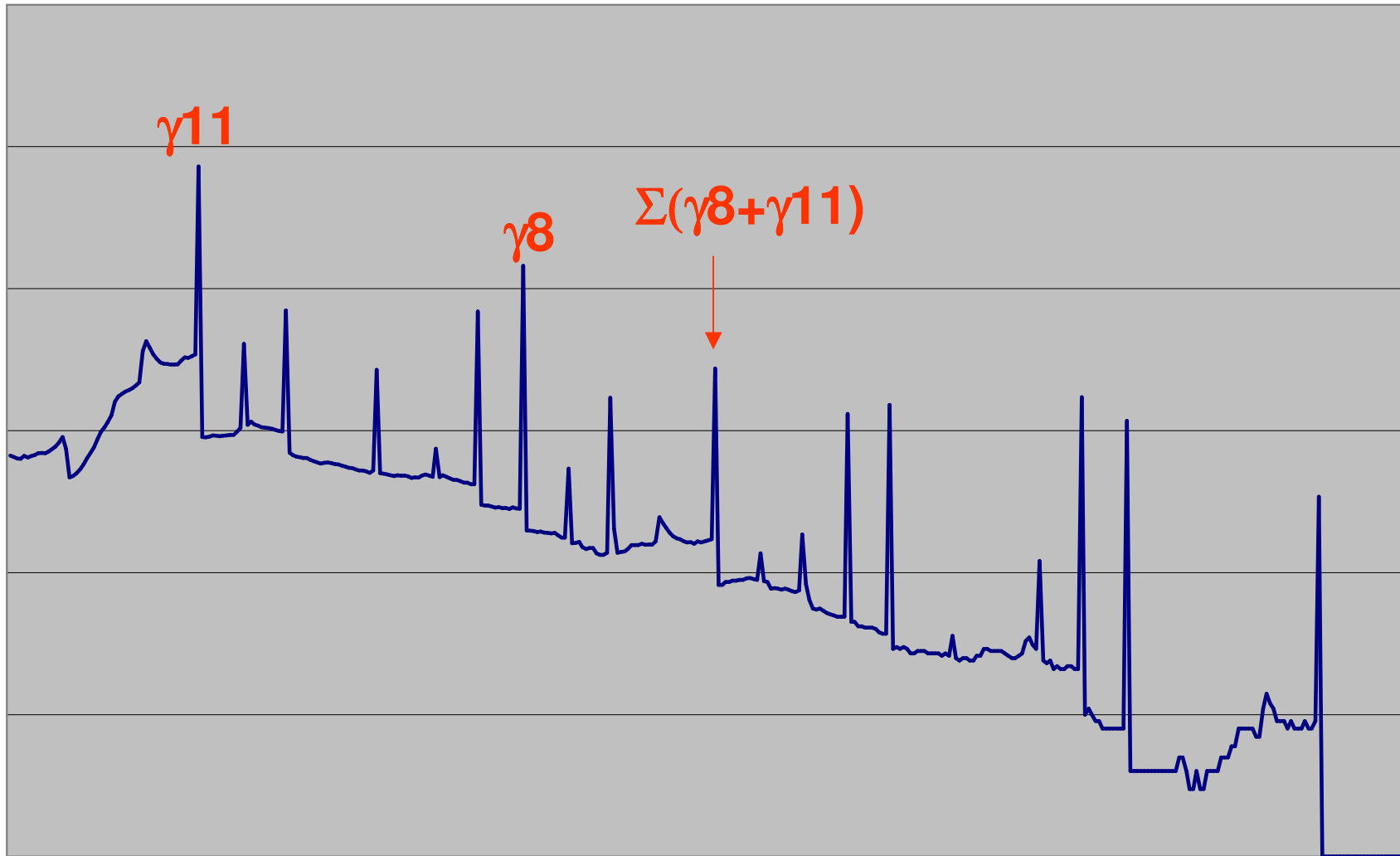


RNG 2





Response function for virtual radionuclide





Volume (cm ³)		GeLi 30%		GeLi 12%	planar 50%	Ratio 78cm ³ / 14 cm ³	Ratio 78cm ³ / 33 cm ³	Ratio 78cm ³ / 1000 cm ³
	Energy (keV)							
Ba-133	81	1.21	1.14	1.054	1.30	1.07	1.14	1.23
	303	1.08	1.05	1.015	1.23	1.14	1.17	1.21
	356	1.07	1.04	1.012	1.15	1.07	1.11	1.14
Co-60	1173	1.14	1.09	1.033	1.14	1.00	1.05	1.10
	1332	1.13	1.1	1.034	1.15	1.02	1.05	1.11

∅ (cm)	4.2	4.2	9.0	5.0
height (cm)	1.0	2.4	15.72	4.0
volume (cm ³)	13.9	33.3	1000	78.5