A simulation approach to evaluating the minimum detectable activity of coincidence gamma-ray spectrometers

2025-10-29

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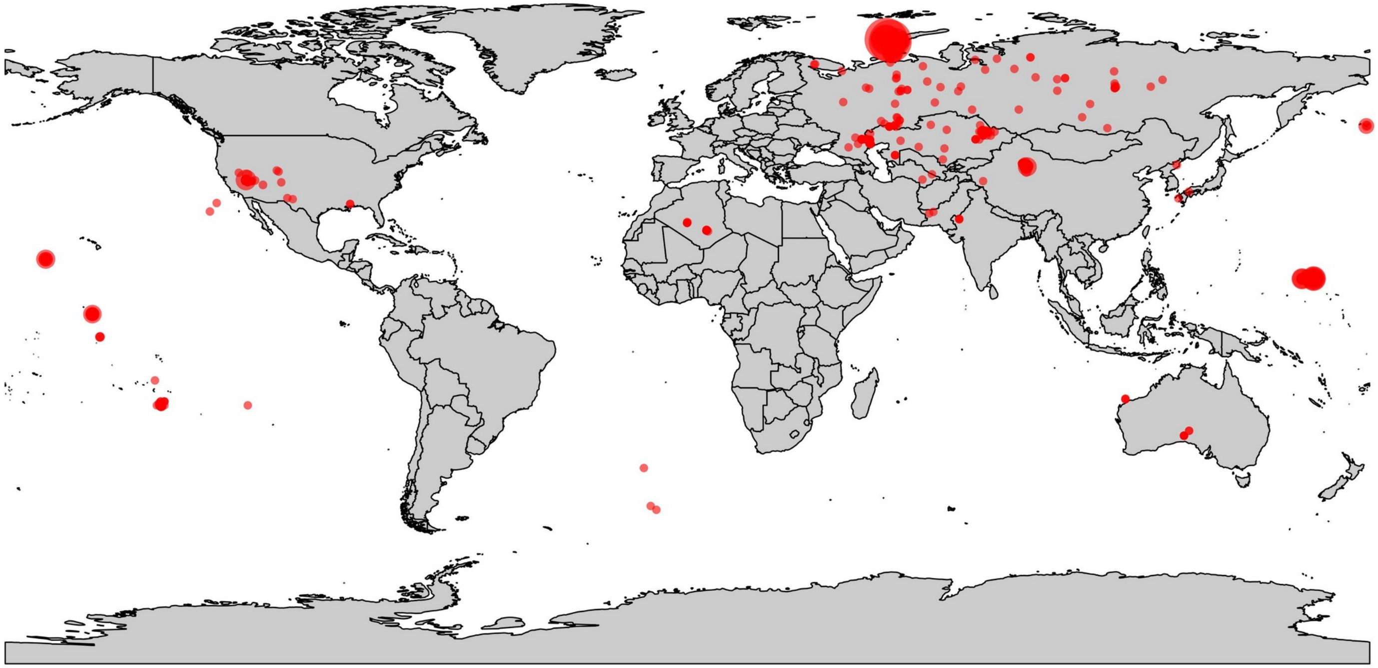
Introduction

PhD student in applied nuclear physics
Uppsala University
Started 2025

Alva Myrdal Center (AMC) for Nuclear Disarmament

Collaboration with the Swedish Defence Research Agency (FOI):
	Coincidence Spectrometry for Radionuclide Monitoring (CoSpeR)

Introduction



~2000 nuclear explosions

Introduction

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- Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO)
- International Monitoring System (IMS)

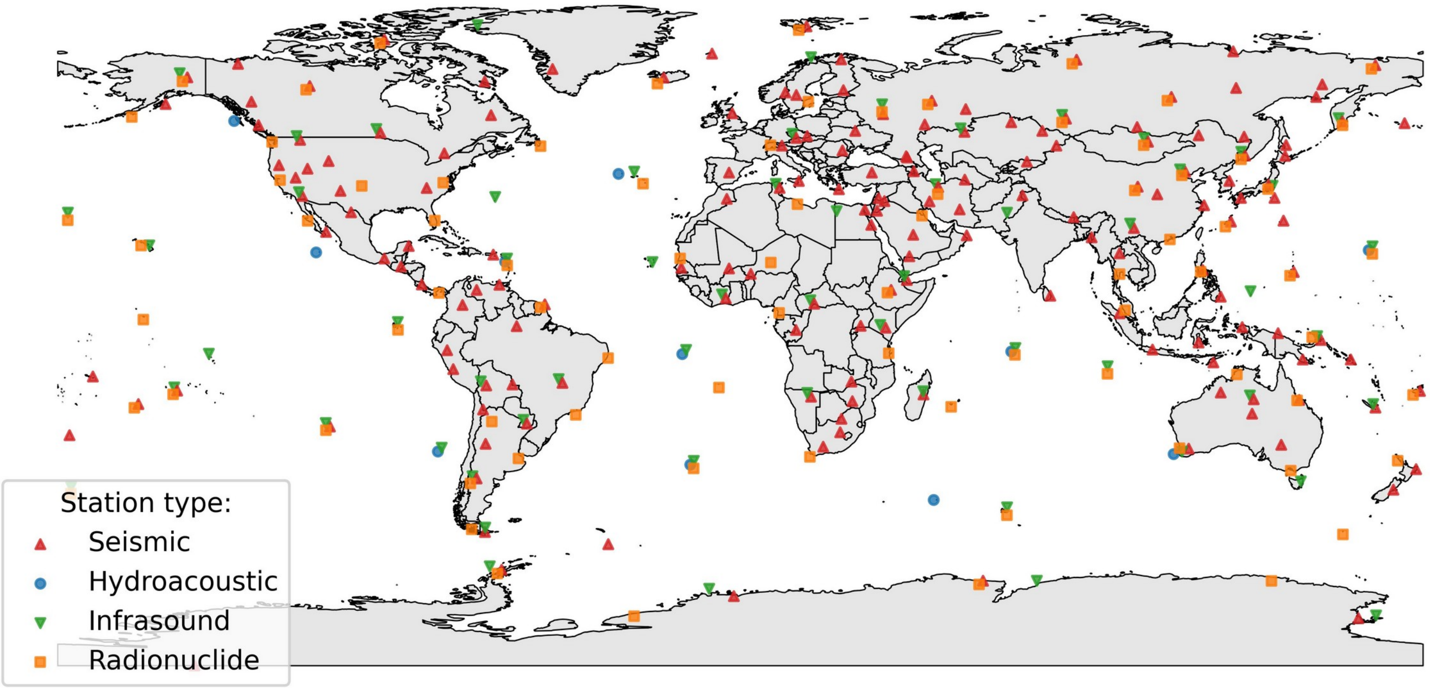
CTBTO
PREPARATORY COMMISSION

Infrasound monitoring, Greenland

Seismic monitoring, Niger

Radionuclide monitoring, Germany

Introduction



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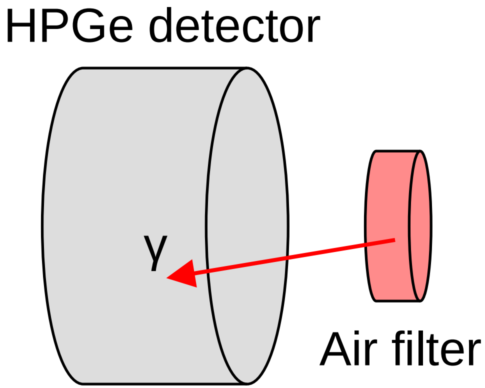
Air sampler at UU



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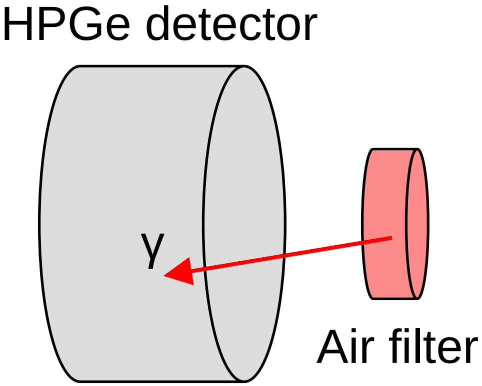

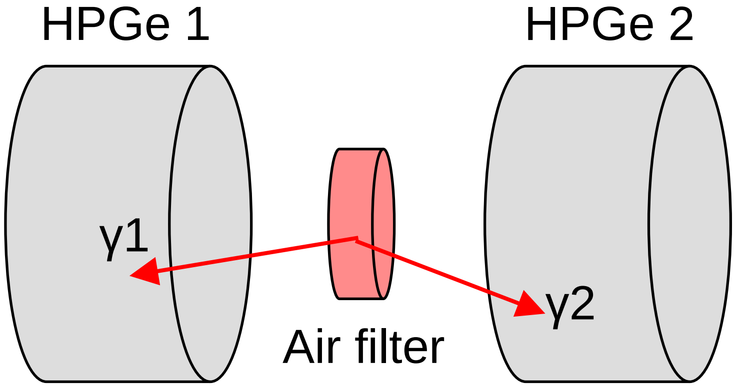

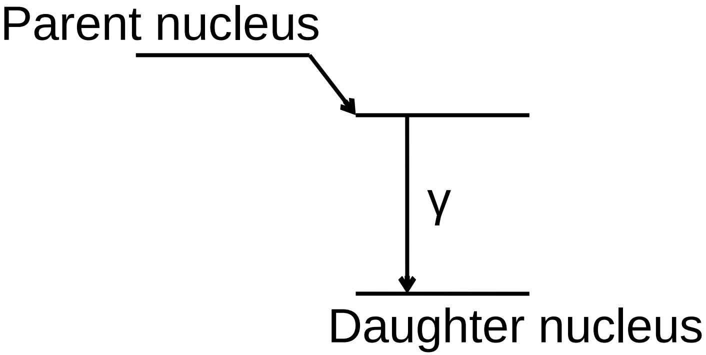

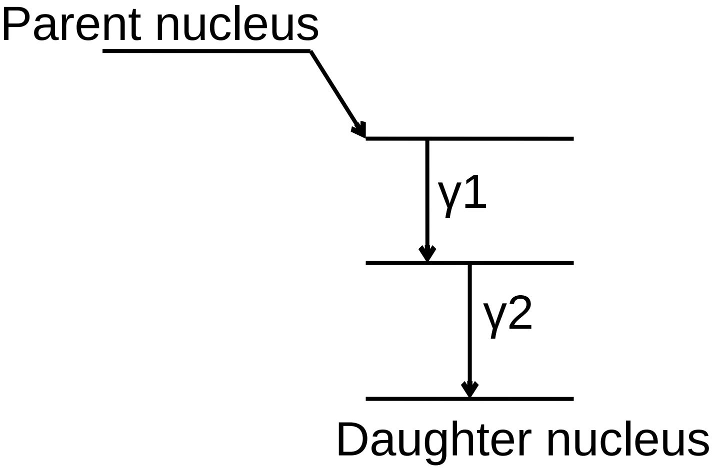

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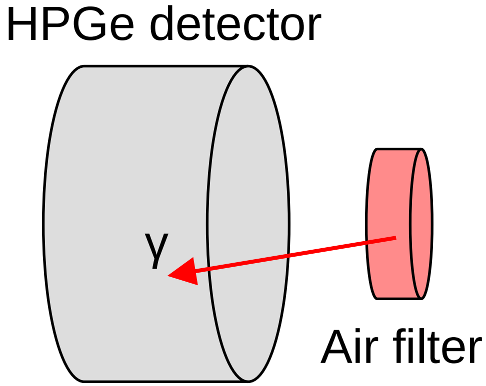

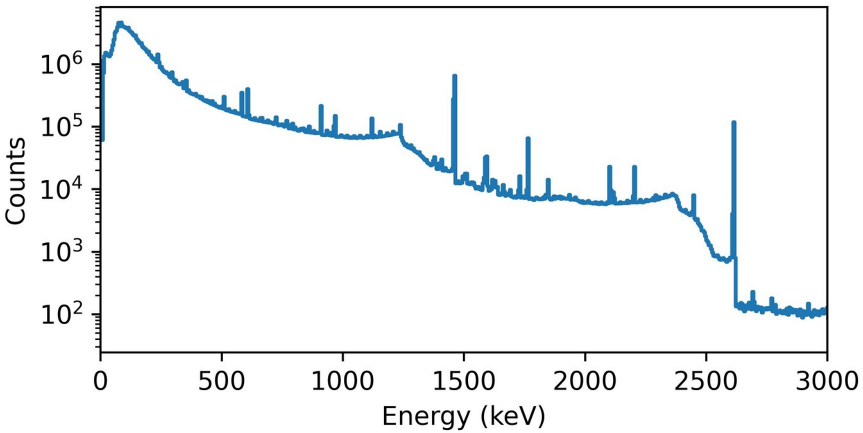

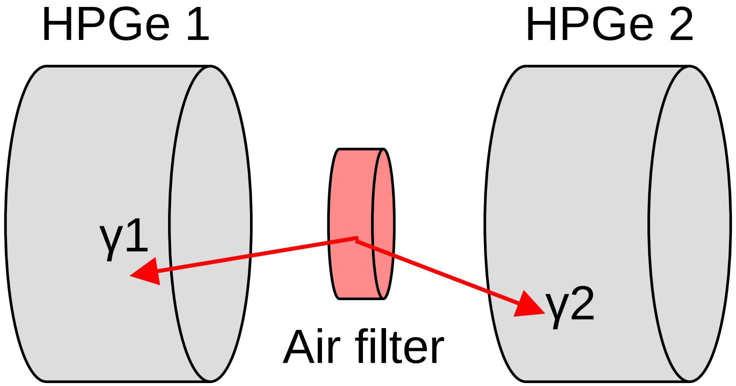

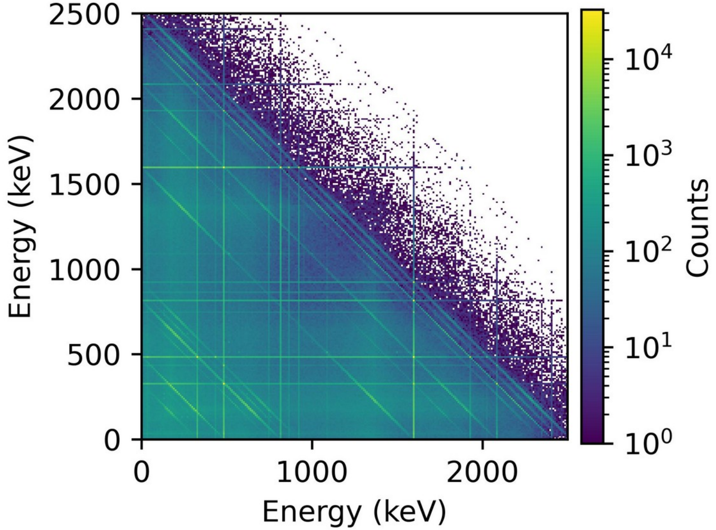

Introduction

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Minimum detectable activity:

Detection limit $L_D \approx 4.65\sqrt{B}$ for large B

$$MDA = \frac{L_D}{\varepsilon_{\gamma\gamma} I_{\gamma\gamma} t}$$

Background counts

Efficiency Intensity Measurement time

Goal: develop method to simulate MDA for coincidence detectors in GEANT4 A SIMULATION TOOLKIT

Simulating background radiation

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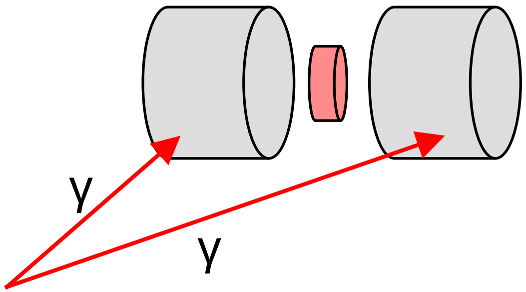
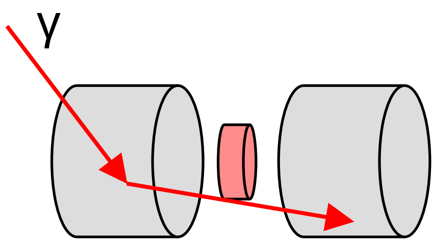
Coincidence background radiation:



Low probability



- Depends on environment!
- Approximation: <u>isotropic and uniform</u>

Simulating background radiation

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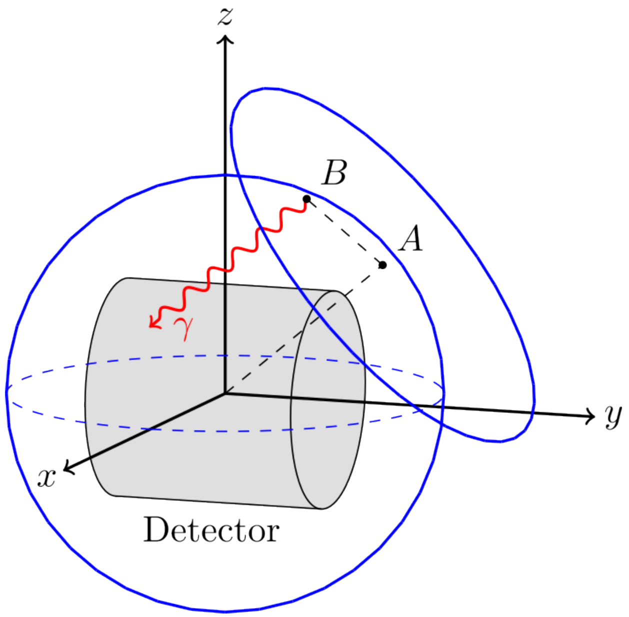
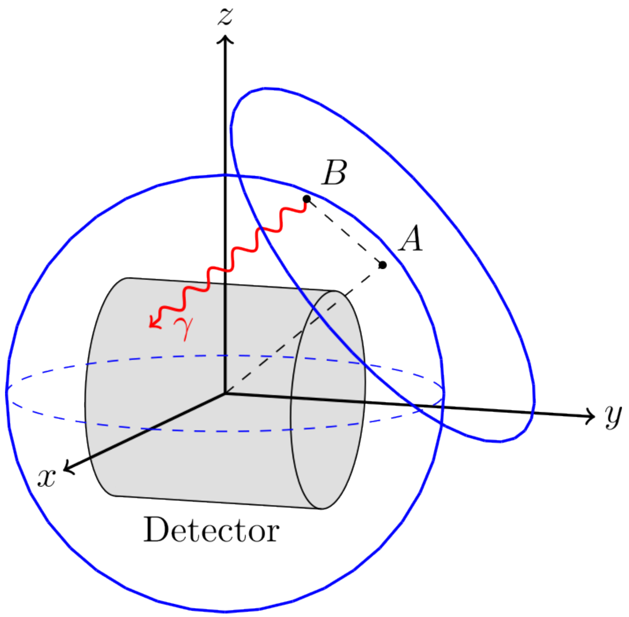
A background model:



Simulating background radiation

A background model:



- Uniform fluence inside sphere:

$$\psi = \frac{N_\gamma}{r^2 \pi}$$

Number of gammas

Radius

- Radius can be adjusted to fit detector
- Computationally efficient
- But what energies should the gamma rays have?

Simulating background radiation

Response function:

$$c(E)=\int_0^{\infty} R(E,E')\,s(E')\,dE'$$

Measured spectrum

Simulated response function

Unknown source spectrum

Response matrix:

$$c=R\,s$$

Simulating background radiation

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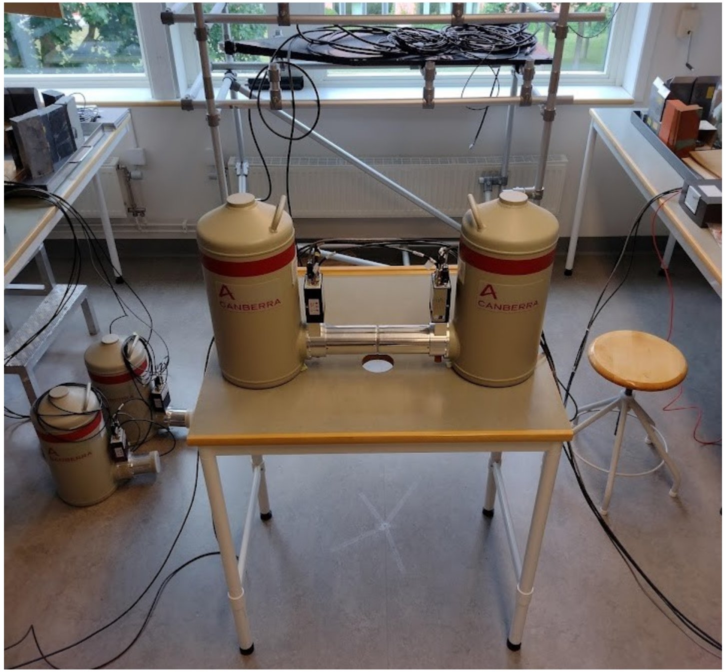
Measuring spectra in two cases:

Unshielded at UU

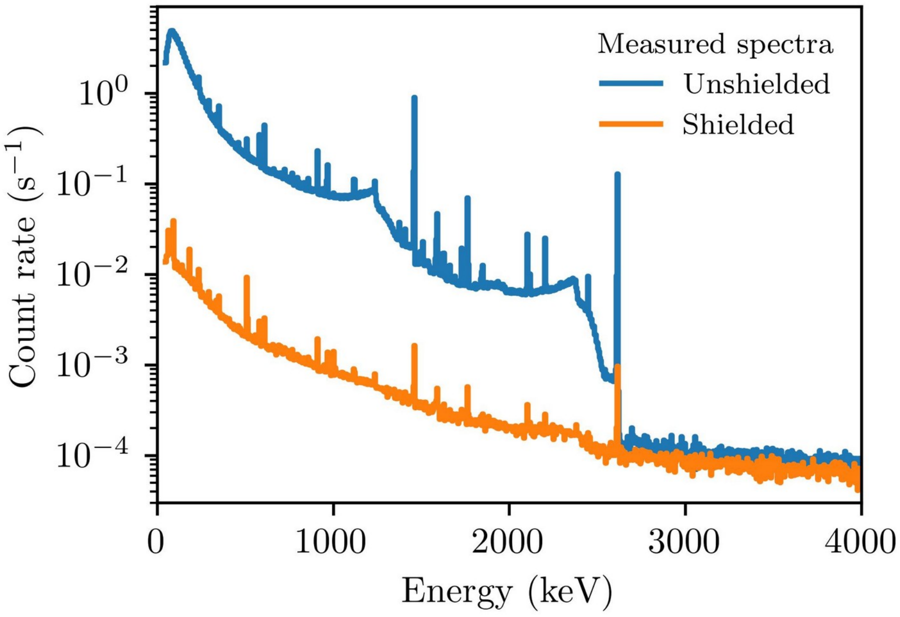


Shielded at FOI

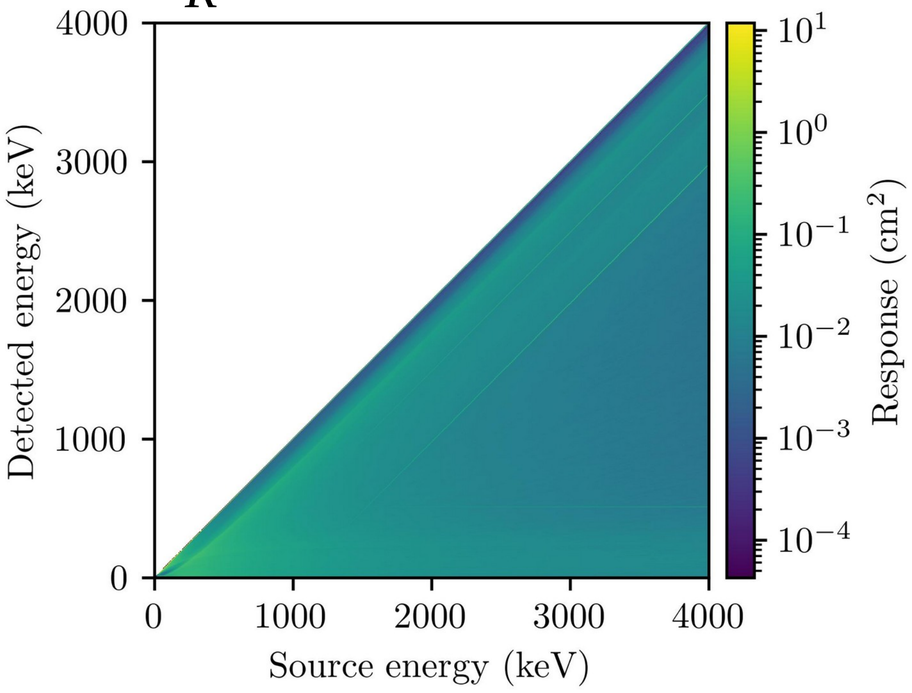
Simulating background radiation

Recall that $c = R\,s$

c



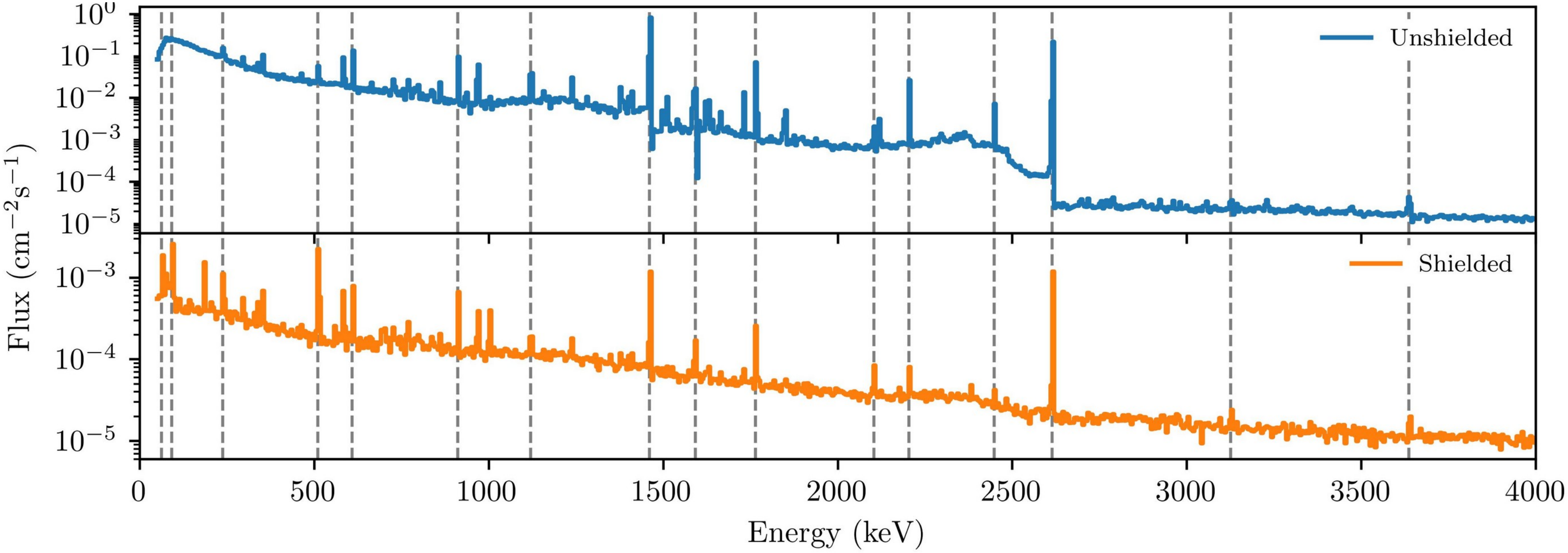
R



Simulating background radiation

Recall that $c = R\,s$

s



Simulating background radiation

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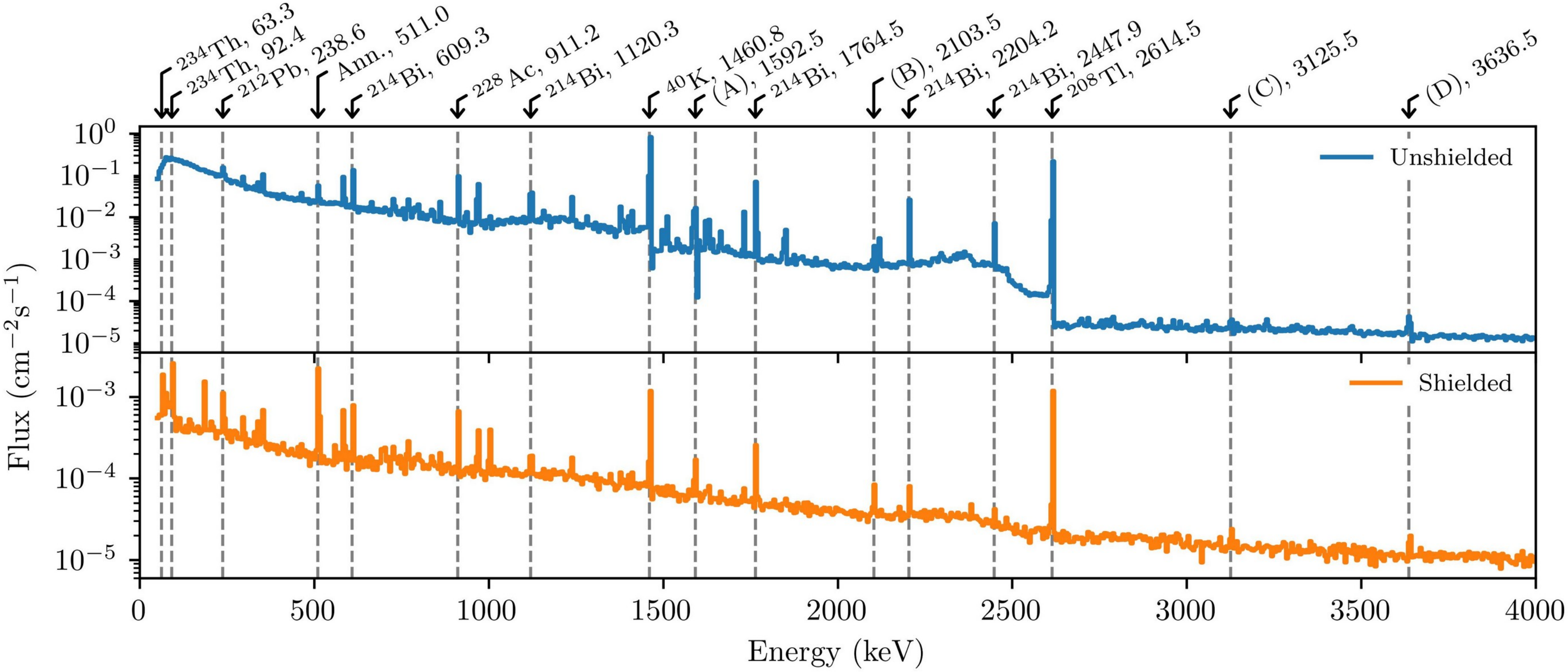
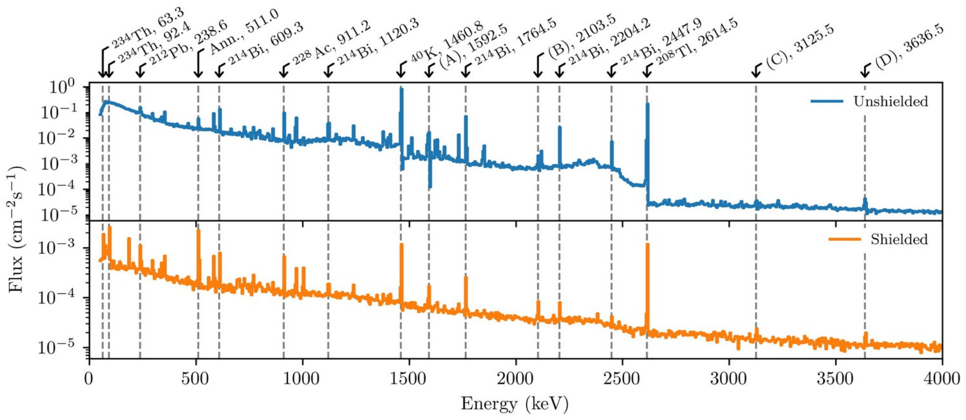
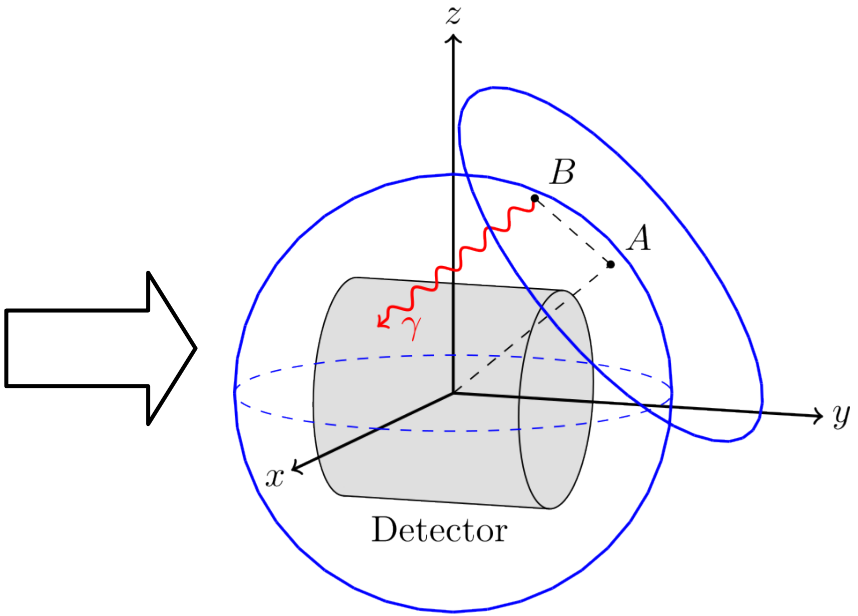
Recall that $c = R\,s$



Simulating background radiation

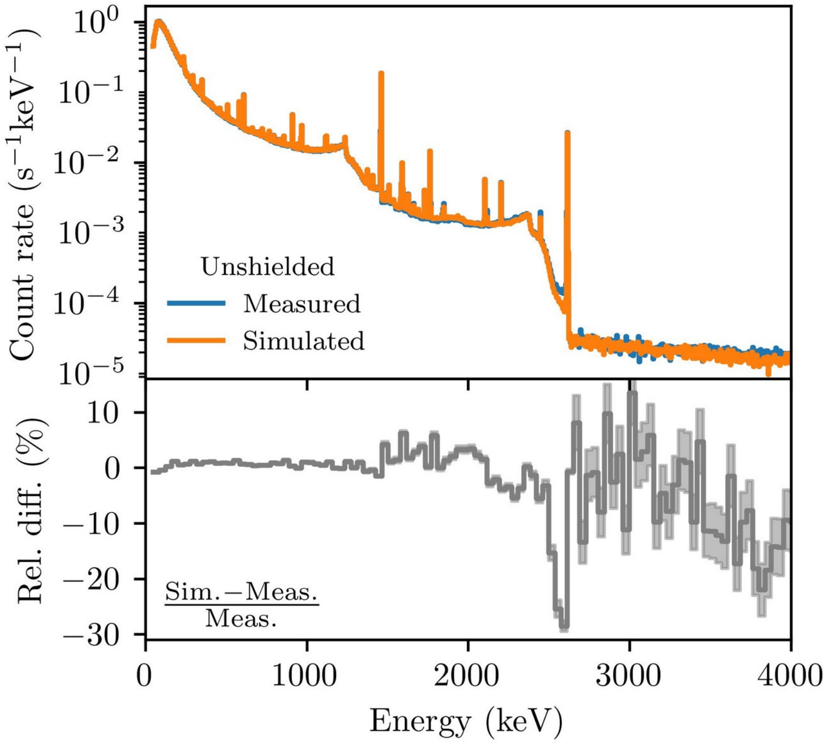
Comparing simulations to measurements





Simulating background radiation

Comparing simulations to measurements (1D)



Simulating background radiation

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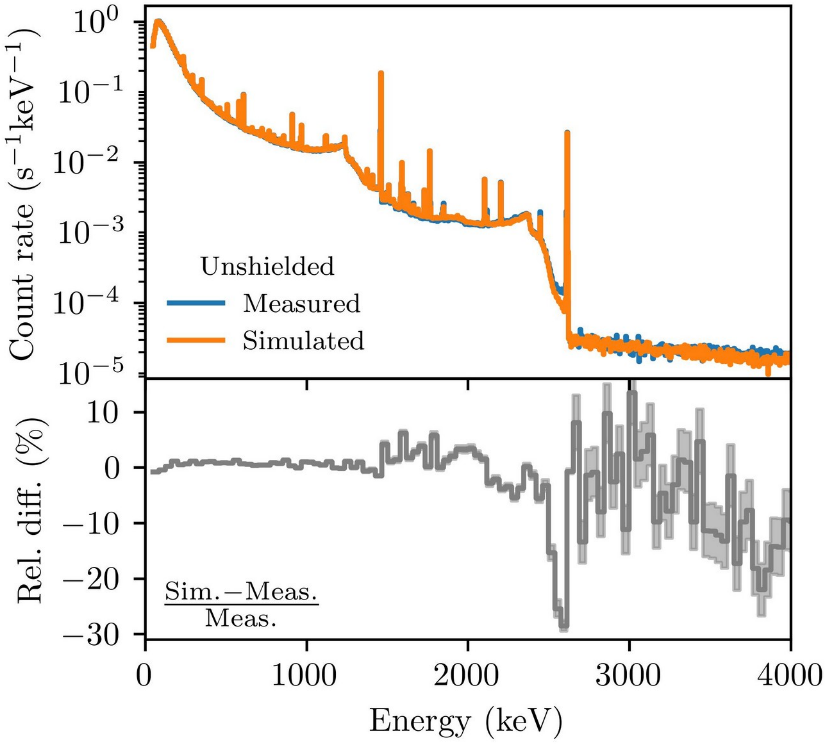
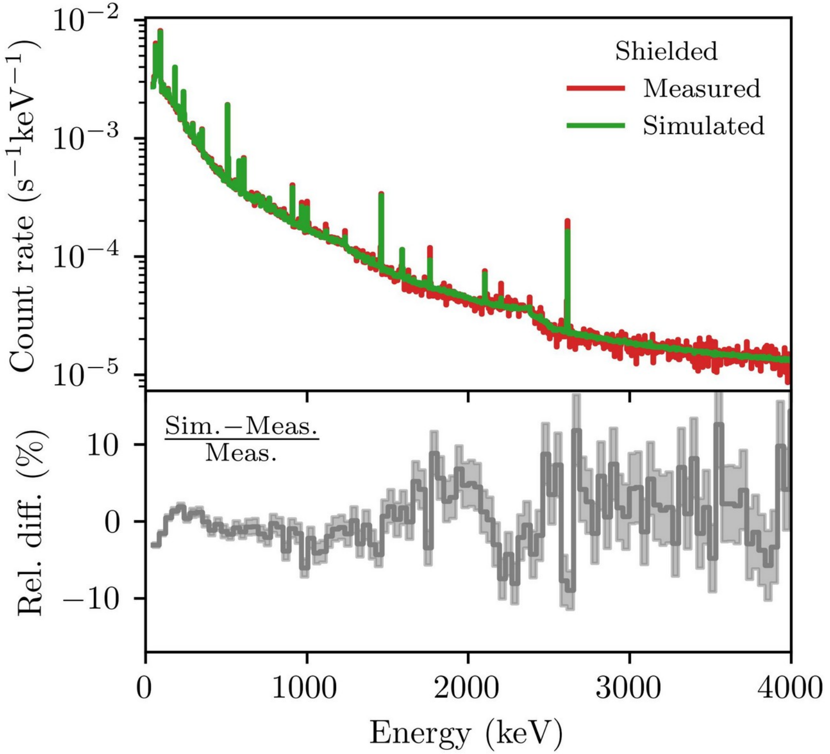
Comparing simulations to measurements (1D)





Simulating background radiation

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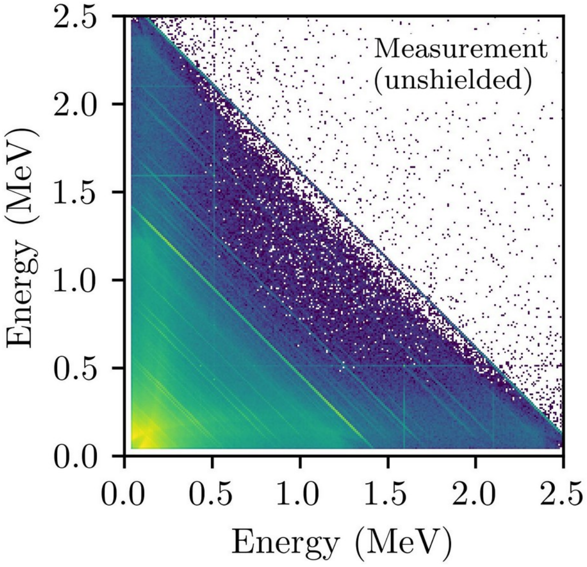
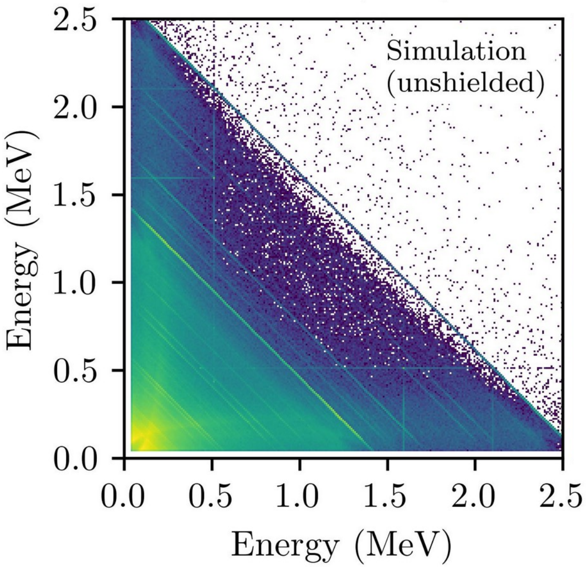
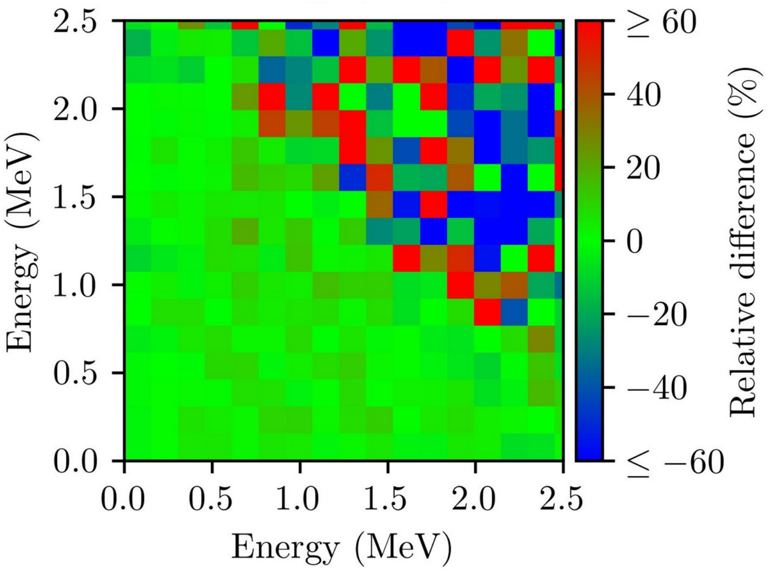
Comparing simulations to measurements (2D)



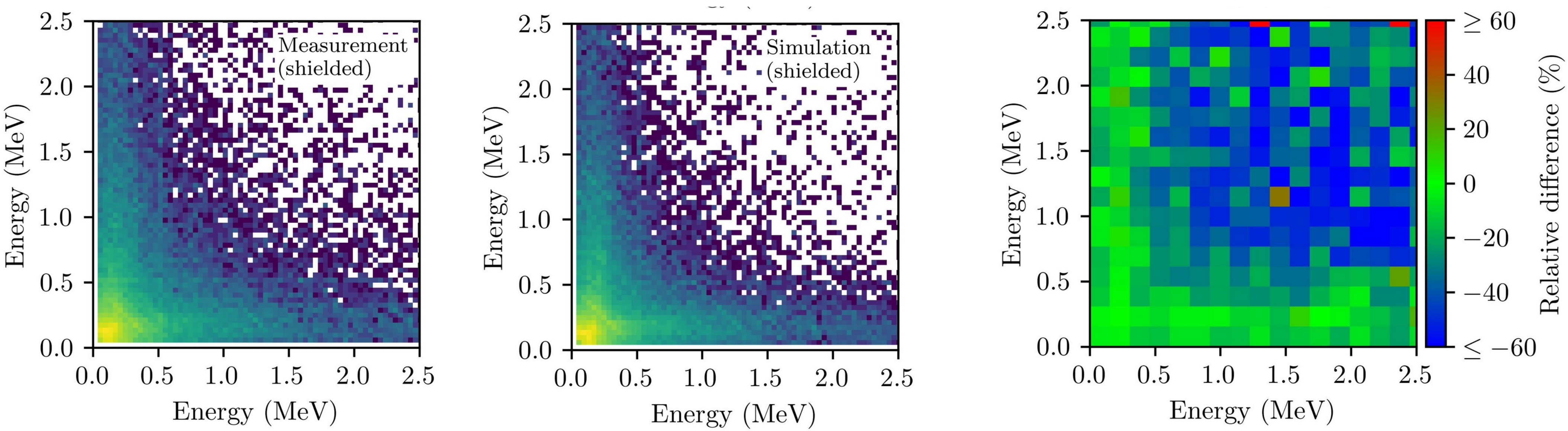




Works well for
E1 + E2 < 2614 keV

Simulating background radiation

Comparing simulations to measurements (2D)



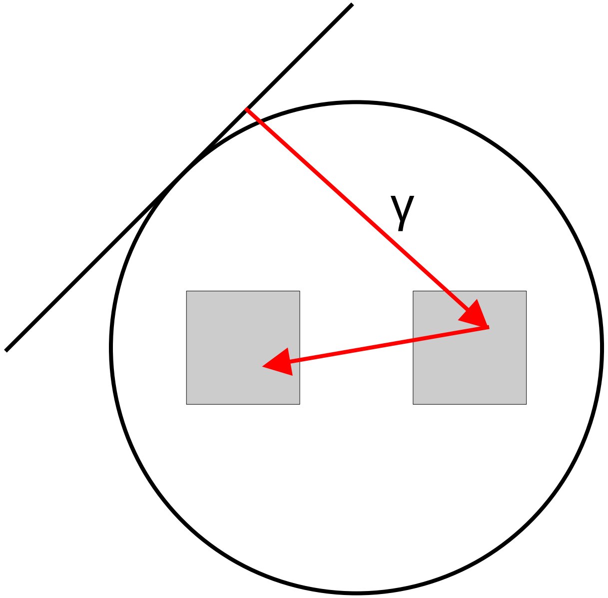
Simulation underestimates by ~40% above 500 keV

Example

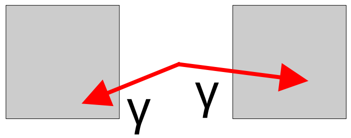
Measure La-140 point source
Two 70x70 mm cylindrical detectors, 1 mm of Al surrounding Ge, point source
How does MDA vary with distance between the detectors?

$$MDA = \frac{L_D}{\varepsilon_{\gamma\gamma} I_{\gamma\gamma} t}$$

<u>Background simulation:</u> L_D

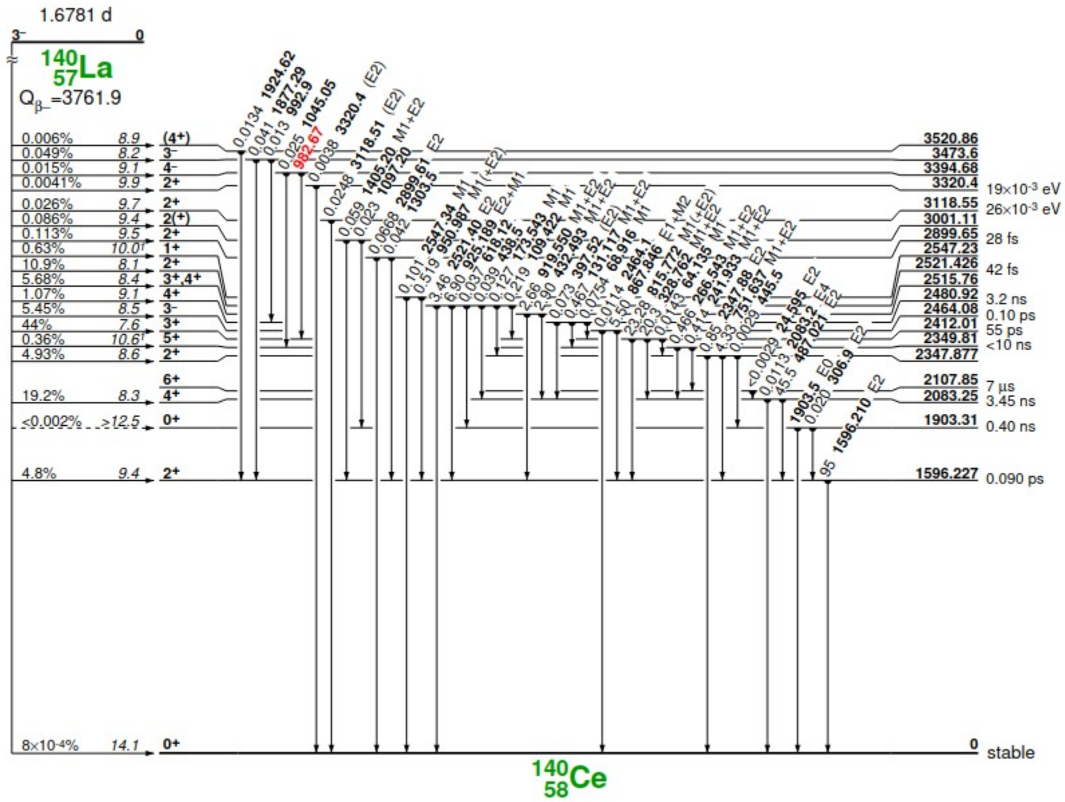


<u>Radionuclide simulation:</u> $\varepsilon_{\gamma\gamma} I_{\gamma\gamma}$



Example

La-140
Most promising γγ-coincidences (keV): [329, 487]; [816, 1596]; [487, 1596]



Example

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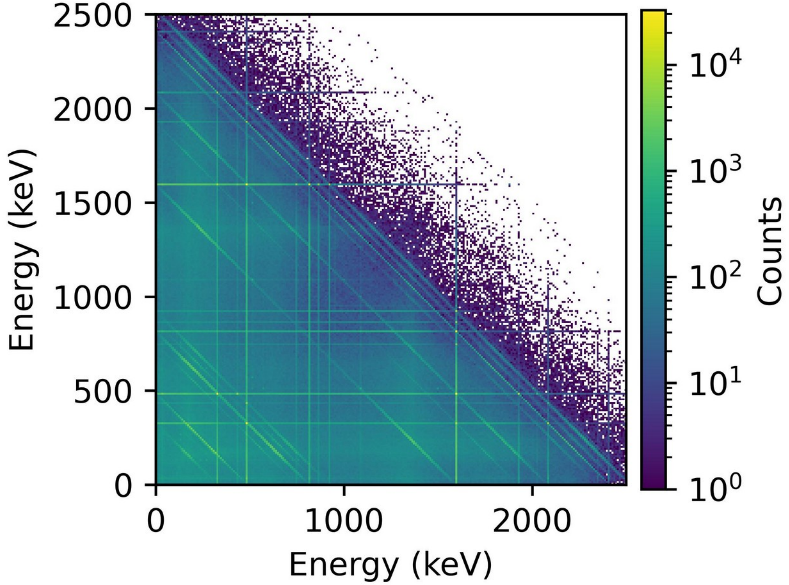
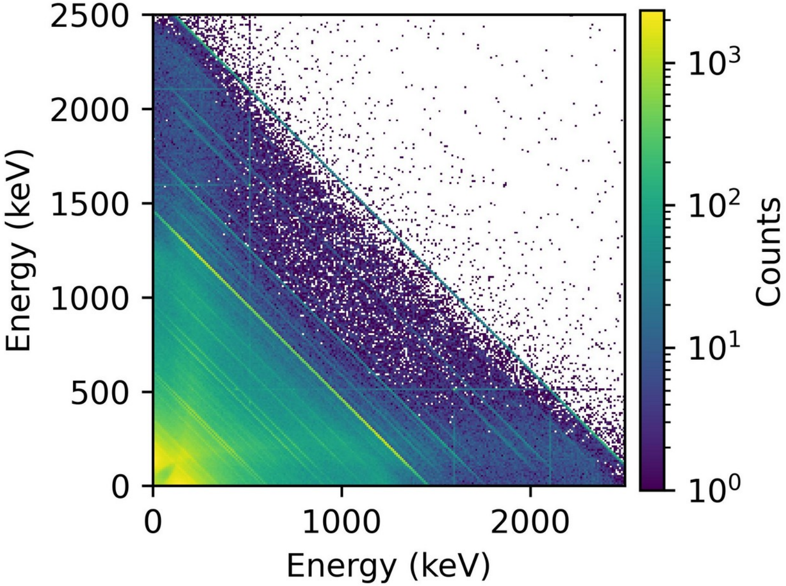


Radionuclide simulation



Background simulation

$\varepsilon_{\gamma\gamma} I_{\gamma\gamma}$

L_D

$$MDA = \frac{L_D}{\varepsilon_{\gamma\gamma} I_{\gamma\gamma} t}$$

Example

$$MDA = \frac{L_D}{\varepsilon_{\gamma\gamma} I_{\gamma\gamma} t}$$

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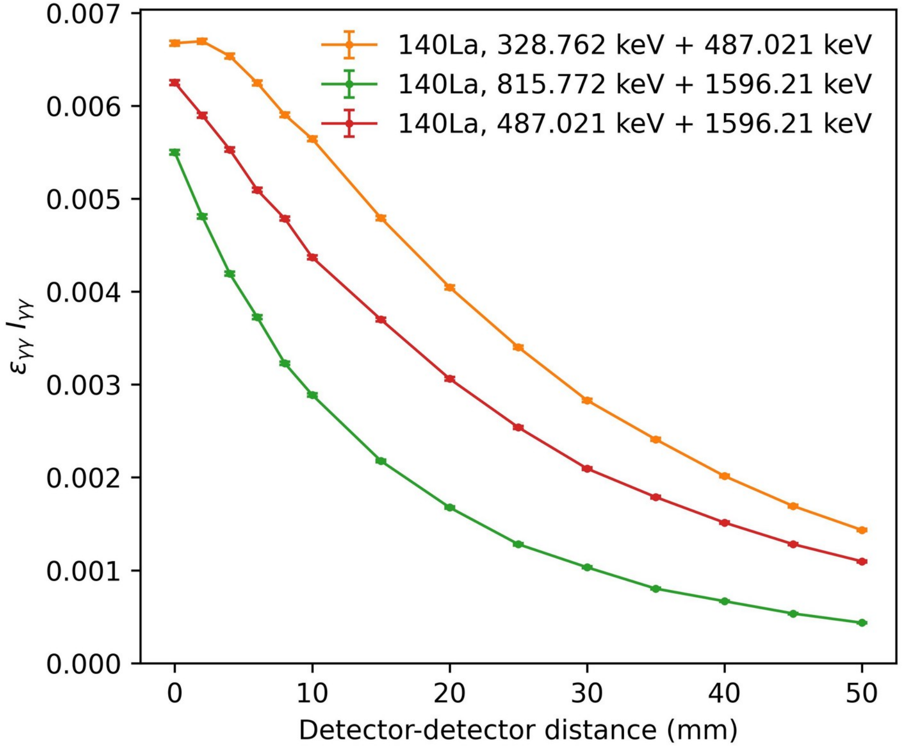
(La-140, t = 1 day, no decay correction, unshielded environment)



Example

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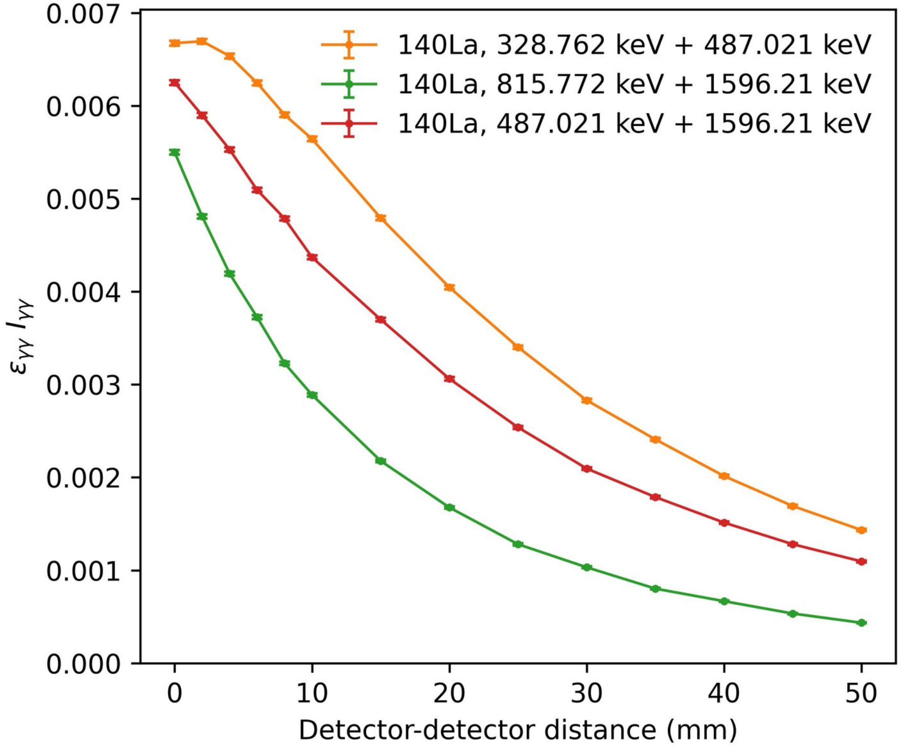

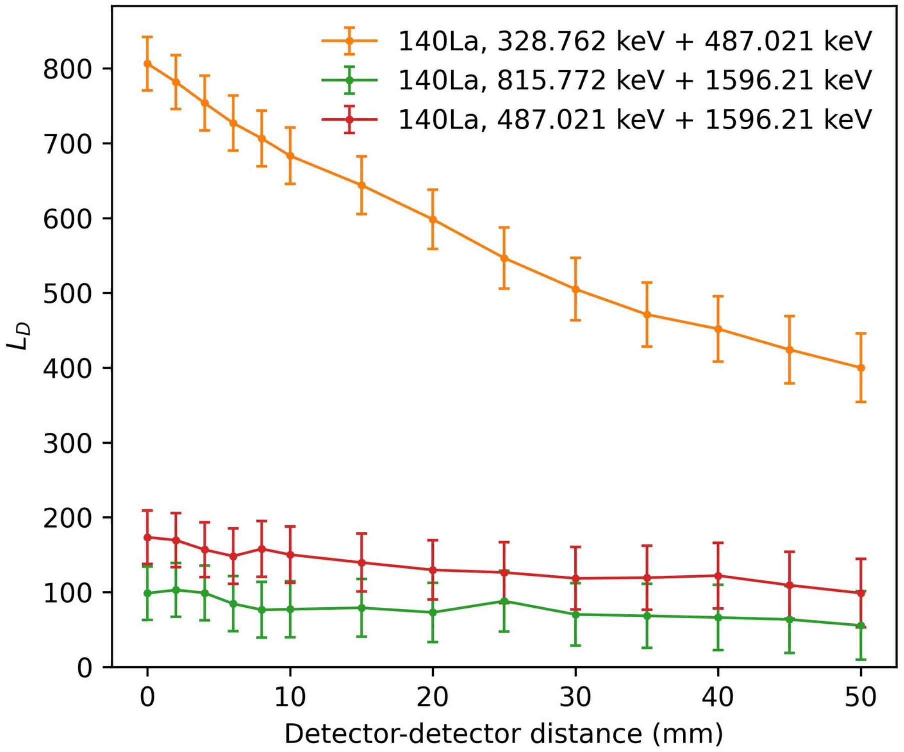

Example

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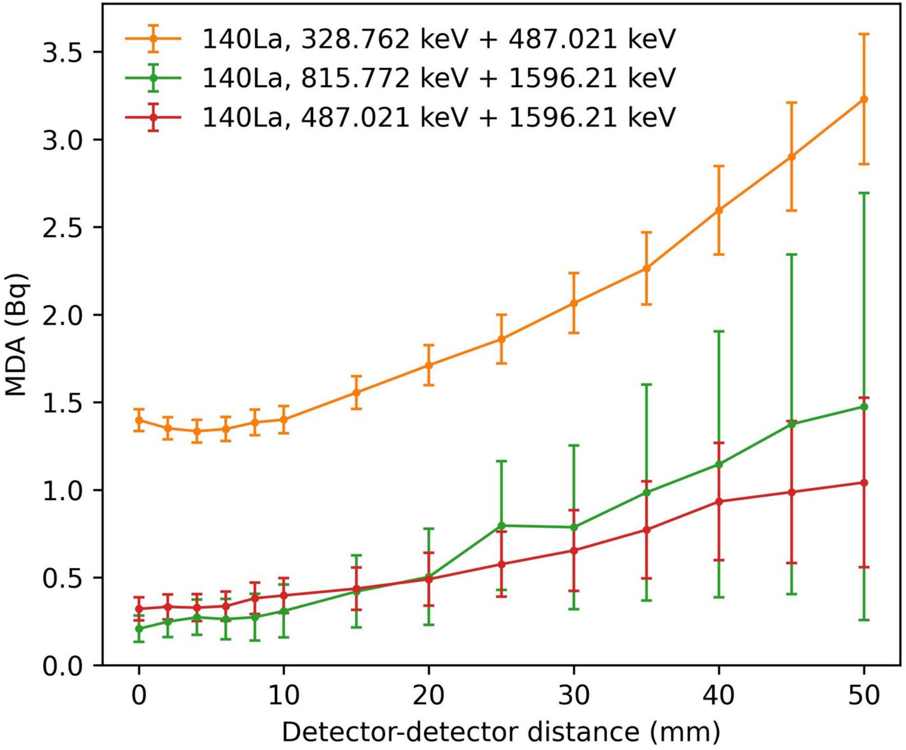

Example

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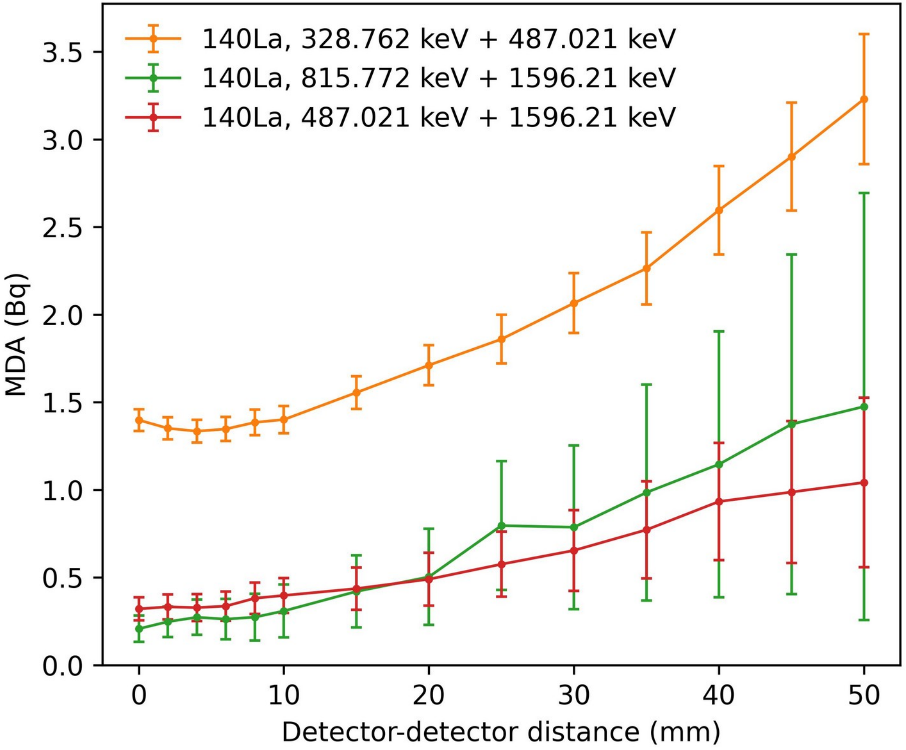

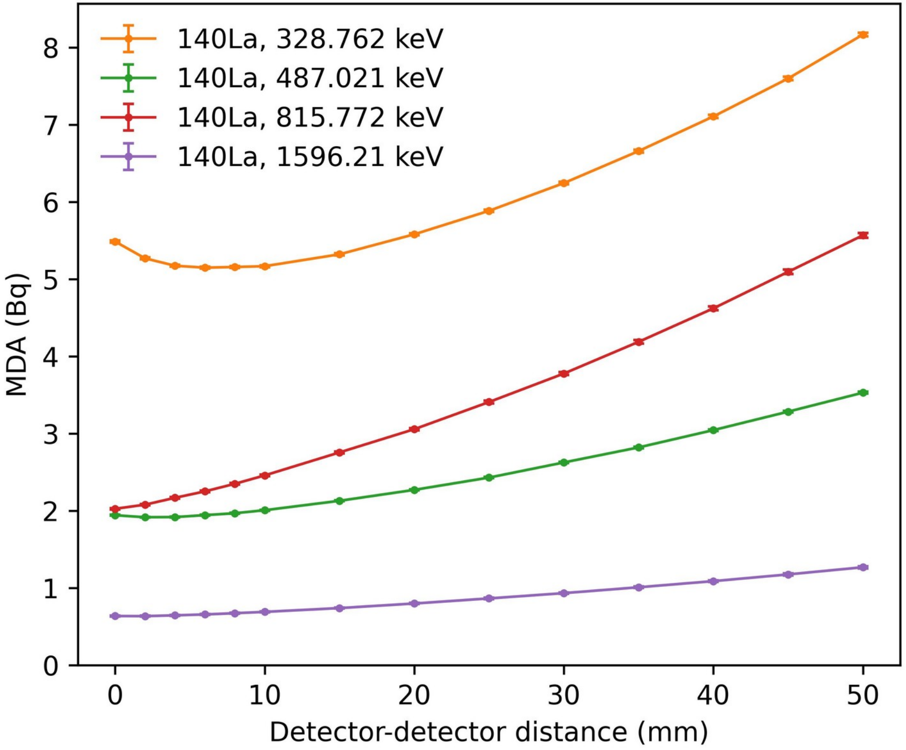

Next steps

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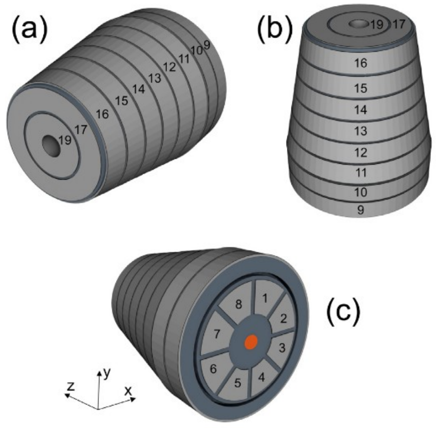
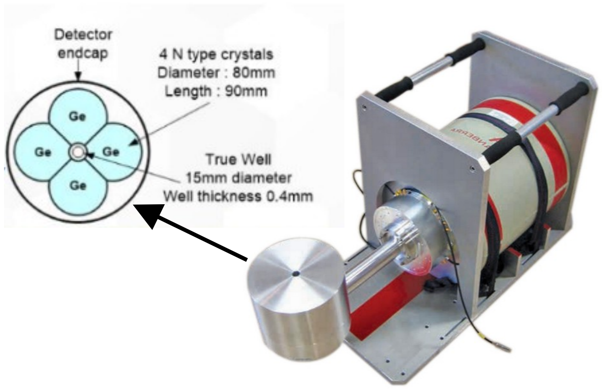
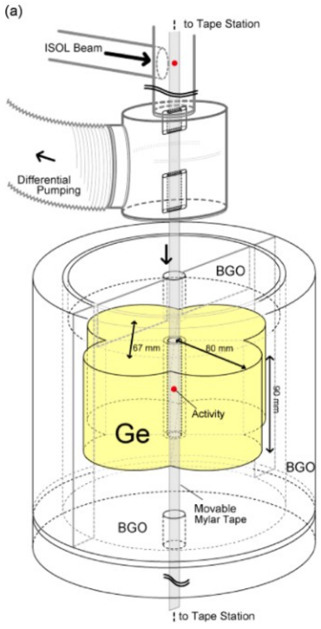
- More complex detectors







F.J. Pearce et al.
10.1016/j.nima.2021.166044

Mirion Technologies

H. Hayashi et al.
10.1016/j.nima.2014.02.012

Next steps

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- More complex detectors
- Other radionuclides
    - Candidates: Ba-140/La-140, Mo-99, Te-132/I-132, I-131, I-133, I-135

Next steps

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- More complex detectors
- Other radionuclides
  - Candidates: Ba-140/La-140, Mo-99, Te-132/I-132, I-131, I-133, I-135
- What detector achieves the lowest MDA?

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The end

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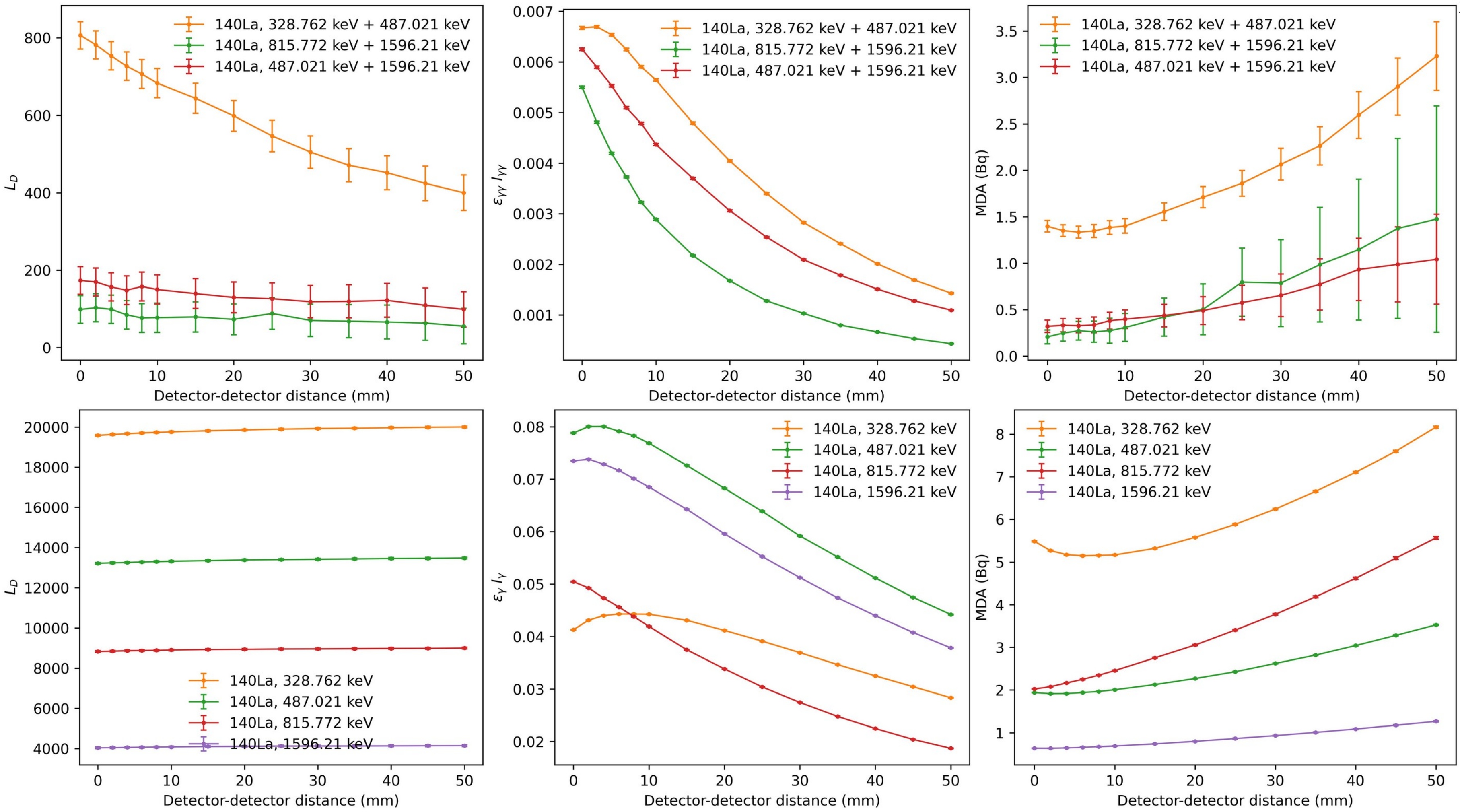
Backup slides

Example: simple cylindrical detectors



The alternatives

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- Currie formula (Poisson-normal) $L_C = k_\alpha \sqrt{2B}$ $L_D = k_\alpha^2 + 2 k_\alpha \sqrt{2B}$

- Stapleton approximation $L_C = \frac{k_\alpha^2}{2} + k_\alpha^2 \sqrt{2(B+0.4)}$ $L_D = L_C + \frac{k_\alpha^2}{2} + k_\alpha \sqrt{\frac{k_\alpha^2}{4} + L_C + 2B}$

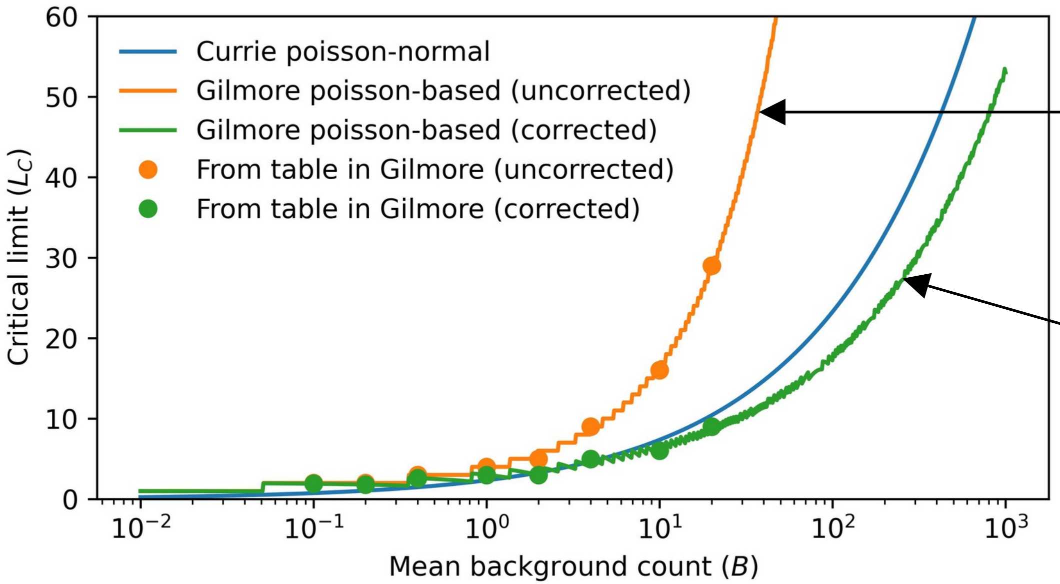
- ISO standard 19929 (MDA directly) $MDA = w \frac{k^2 + 2k\sqrt{2B}}{1 - k^2 var(w)}$ $w = \frac{1}{\varepsilon I t}$

- Poisson definition (as in Gilmore)

- Poisson definition (“the correct way”)

Gilmore definitions

- Gilmore uses Poisson-normal (Currie) and Possion definition
- They do not converge for high counts!

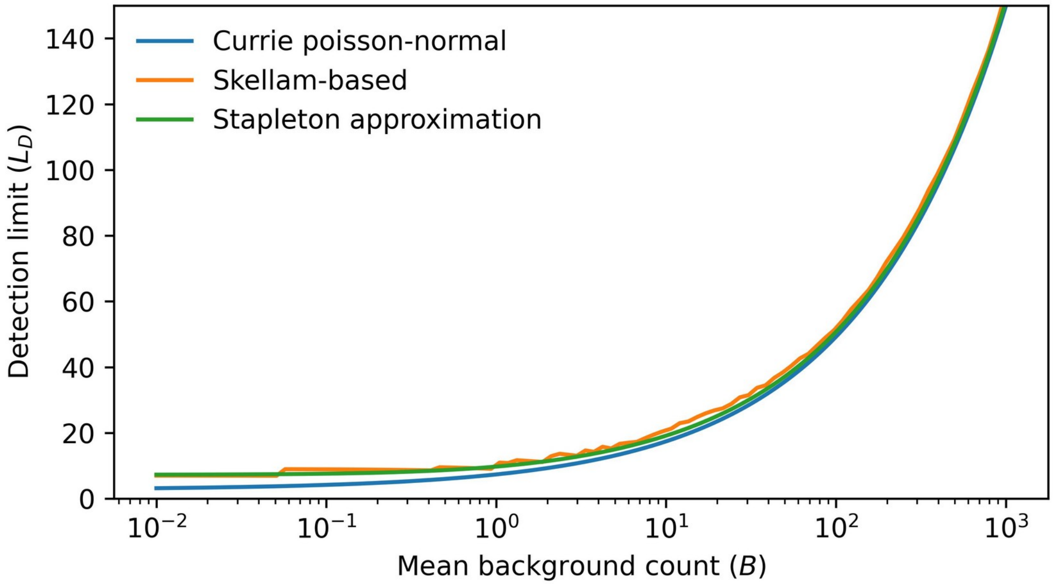


Careful! Gilmore is not consistent with definitions, one needs to subtract B from L_C here

Does not converge, even after correction

Detection limits

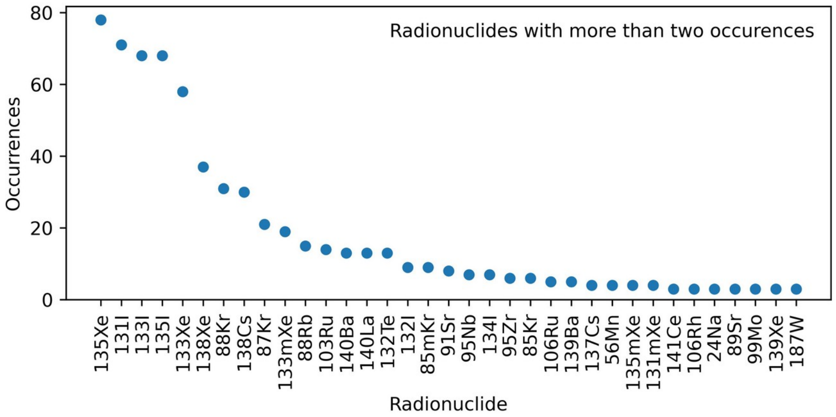
- More or less the same

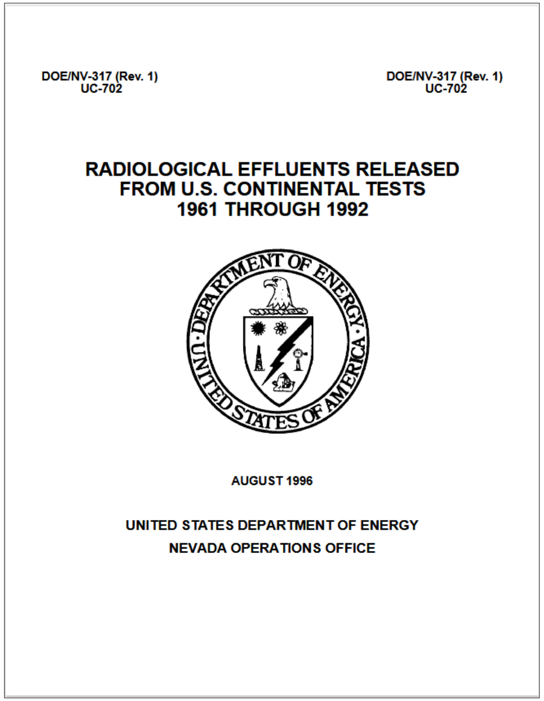


Radionuclides

Which radionuclides?
- Coincident gamma emission
- Good half-life
- Produced in tests
- Beneficial if well-known

Shortlist:
- Ba-140/La-140
- Te-132/I-132
- Mo-99
- I-131
- I-133
- I-135





Unfolding background spectrum

Implementation in Geant4: