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# feign: a Python package to estimate geometric efficiency in passive gamma spectroscopy measurements of nuclear fuel

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**Software**

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## Summary

The operator declarations of spent nuclear fuel assemblies are routinely verified for nuclear safeguards purposes to ensure their non-diversion and integrity. Many countries consider the possibility of eventually placing the fuel in a geological repository and prior to this it is expected that the fuel assemblies need to be carefully characterized and verified, for instance using gamma spectroscopy measurements. It can be expected that in connection to such activities, verifying parameters such as burnup (the energy outtake from the nuclear fuel), cooling time (the time the fuel spent outside the reactor after operation), initial enrichment (the amount of fissile material in the fuel before operation) and integrity (whether pins inside the assembly have been manipulated) may become an important task of nuclear safeguards inspectors, since discrepancies may indicate unauthorized activities at the facilities. Ideally, the verification should be done with non-destructive assay systems.

Passive gamma spectroscopy provides a robust and relatively simple method to analyze spent fuel since the characteristics of spent nuclear fuel strongly affect the gamma radiation emitted from the fuel (Jansson, 2002). Lately, passive gamma tomography has also become a possible method to characterize and analyze properties of spent nuclear fuels (Mayorov et al., 2017). In both cases, gamma radiation is measured around the fuel assembly from a distance using one or more collimated detectors with spectroscopic capabilities. Of great interest is the detector efficiency of these systems, i.e., the ratio between number of detected particles and number of particles emitted by the source. The detector efficiency is the product of the geometric efficiency (probability that emitted particles reach the detector region) and the intrinsic efficiency of the detector (probability that the particles are detected).

## Statement of need

The detector efficiency is usually estimated with Monte Carlo simulations, typically using the MCNP particle transport code (Goorley et al., 2012). Monte Carlo simulations of spent fuel passive gamma measurements are extremely time consuming even if variance reduction techniques are applied. This is because the source (the spent fuel assembly) is both highly radioactive and highly attenuating (made of high-density uranium dioxide), and the strong radiation field around the source often makes it difficult to place it near the detectors. In addition, it is not uncommon to use collimators with narrow slits around the detectors, something that makes the simulation of the detection process even more time consuming. Thus, only a tiny fraction of source particles reach the detector.

The time requirements become daunting if the efficiency curves of a large number of assembly configurations are needed, for example when training machine learning algorithms for classification analysis of intact and manipulated fuel assemblies based on the measured gamma spectrum (Elter, Caldeira Balkeståhl, Grape, & Hellesen, 2018). Furthermore, when prototyping with such algorithms, the accuracy of a Monte Carlo code may be unnecessary. One could argue that in collimated passive gamma spectroscopy setups only the uncollided gamma rays contribute significantly to the gamma peaks in the spectrum (if the background is removed), and if the distance between the detector and the source is much larger than the size of the detector, computing the uncollided point-detector response of the setup would be satisfactory to get an estimate of the detector geometric efficiency. Computing the uncollided point-detector flux does not require a transport code such as MCNP, and the task can be solved with a program that feigns to be a transport code such as the one presented here.

# feign

`feign` is a Python package that implements a 2D point-kernel method to estimate the uncollided point-detector gamma flux around a rectangular spent fuel assembly. It is intended for nuclear safeguards specialists and nuclear engineers who want to get a quick estimate on the geometric efficiency in their passive gamma setup. The package relies on NumPy (Walt, Colbert, & Varoquaux, 2011) for data handling and Matplotlib (Hunter, 2007) for plotting the geometry and the results. The user defines the experimental setup: materials, pin types (consisting of nested annular material regions), assembly lattice, detector locations and optionally collimators and additional absorber elements. The program iterates through each lattice position containing source material and calculates the distance traveled in various materials towards the detector point by a gamma-ray emitted from the given lattice position. Based on the user input, the actual source location is either the center of the pin or a randomly selected location inside the pin (the user also sets the number of randomly selected locations per pin, in order to estimate the standard deviation of the traveled distances).

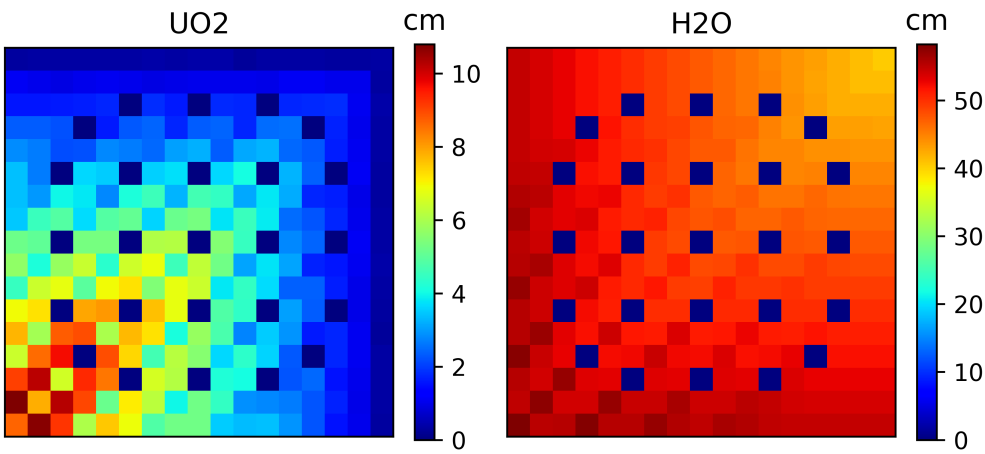


**Figure 1:** Example of distance traveled in uranium-dioxide and water for a 17x17 PWR assembly being measured at the Swedish Central Interim Storage Facility for Spent Nuclear Fuel (Clab). The detector point is facing the upper right corner and is 270 cm away from the center of the assembly. Each pixel represents the distance traveled in a certain material by a gamma ray emitted from that position to the detector.

A traveled distance map can be seen in Fig. 1 for a 17x17 pressurized water reactor (PWR) fuel assembly measured at the passive gamma spectroscopy station of the Swedish Central

Interim Storage Facility for Spent Nuclear Fuel (Clab) as described by Vaccaro et al. (2016). The detector point is facing the upper right corner. Based on the traveled distance maps and user-provided mass attenuation coefficient data, the program evaluates the probabilities $P_i(E)$ (or point-flux per source particle)

$$P_i(E) = \frac{1}{4\pi R_i^2} \prod_m e^{-\mu_m(E) d_{i,m}}$$

that a gamma ray emitted from position $i$ with energy $E$ hits the detector without collision. $R_i$ is the distance between the source position and the detector, $\mu_m$ is the total attenuation coefficient of material $m$ and $d_{i,m}$ is the distance traveled by a gamma ray emitted from position $i$ through material $m$. A relative contribution map can be seen in Fig. 2 for the same 17x17 assembly. When summing the contributions made by each pin for each energy, one gets the geometric efficiency curve of the system. Fig. 3 illustrates one case when the source locations are the center of the pins and another case when ten source locations were randomly selected in each pin. One can see that the pin center approximation has a lower efficiency as compared to the case with randomly selected source locations inside the pin. This is due to the fact that assuming all emissions originate from the center of the pin overestimates the traveled distances (thus underestimating the geometric efficiency).

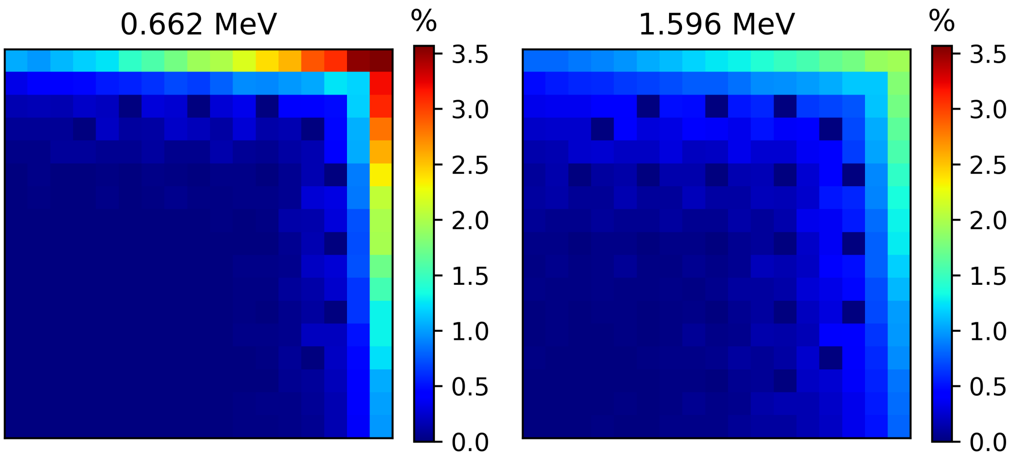


**Figure 2:** Example of contributions made by a pin position to a detector facing the corner of a 17x17 PWR assembly at Clab. Each pixel represents the relative contribution that a gamma ray emitted from that position directly hits the detector.

The program makes several approximations, which limit its areas of application. These approximations and the rationale behind them are the following:

- The program is limited to 2D geometries. For a long collimator with a narrow horizontal slit that is placed in front of the detector, the axial dependence is negligible.
- The build-up factor is neglected. If the detector has a high energy-resolution, then it becomes a valid approximation to consider that for a given gamma peak only photons directly hitting the detector can contribute, and photons participating in scattering reactions will contribute only to the background, which ideally should be removed during the analysis of the spectrum.

For typical spent fuel passive gamma spectroscopy setups, `feign` will produce a reliable estimate of the geometric efficiency curve. Even where its approximations are not valid, the package can be used as a fast way to estimate the uncollided point flux in order to aid setting up variance reduction methods in Monte Carlo calculations (e.g., importance values or weight windows).

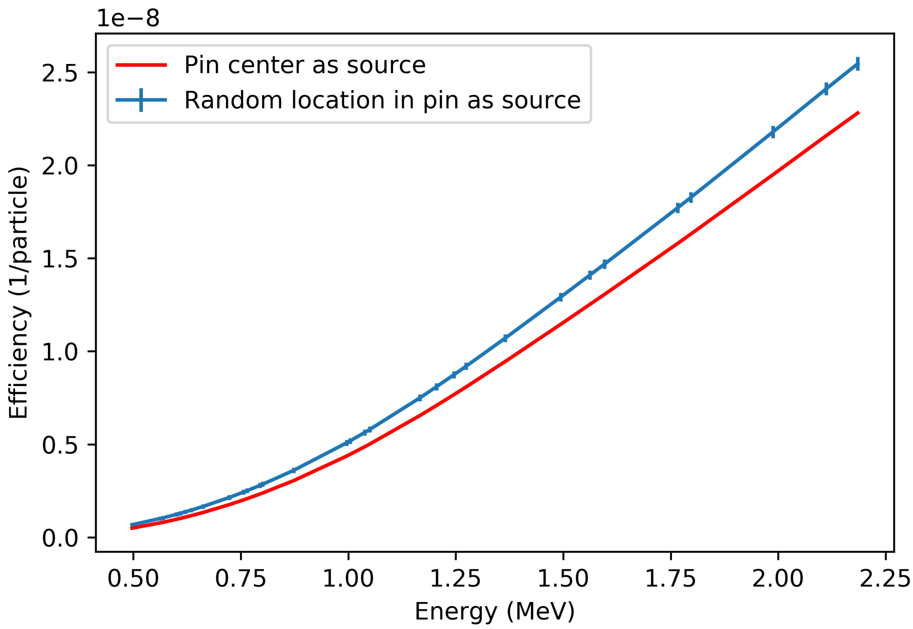


**Figure 3:** Example geometric efficiency curve calculated for a 17x17 PWR assembly being measured at Clab. Errorbar represents three standard deviations.

# Acknowledgements


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