



Surrogate models and Bayesian inference for the characterization of radioactive waste packages by active photonic interrogation

Context

The medium- and long-term management of waste packages from the nuclear industry requires verification of their radiological content using non-destructive characterization methods based on nuclear measurements. This involves detecting, locating, and quantifying nuclear material [1]. Passive techniques use the radiations directly emitted by the material, while active techniques use interrogating radiations (neutrons or photons) and exploit secondary particles produced by reactions induced in the material.

Complementary to other techniques, such as high-energy imaging, active photonic interrogation (API) is a method of choice for characterizing the contents of large concrete-encased packages. The principle is as follows: high-energy photons (>9 MeV) produced by a linear electron accelerator (LINAC) penetrate deep into the package and induce fission in the nuclear material. The radiation emitted by the radioactive fission products is detected, in particular those that emit high-energy gamma rays, which are themselves able to escape from the package. Knowing the characteristics of the interrogating beam (energy, intensity, direction), it is possible to reverse the problem, i.e., obtain a reaction rate from the measurement of radiation from photofission.

At the IRESNE institute (CEA Cadarache), the Nuclear Measurements Laboratory (LMN) is developing API for the needs of the French agency in charge of nuclear waste management (ANDRA) as well as for characterizing the 870 L concrete waste packages produced by CEA. The laboratory operates an irradiation cell (CINPHONIE) recently equipped with a new linear electron accelerator dedicated to high-energy imaging and API. Studies conducted at the LMN since 2019 have focused on high-resolution gamma spectrometry of short-lived fission products [2], with the aim of detecting and discriminating between different types of nuclear material (e.g., enriched or depleted uranium). This technique is promising but does not allow inspections to be carried out within a realistic timeframe as it requires significant irradiation and measurement times.

A thesis project currently underway is exploring the use of scintillation detectors for the rapid localization of nuclear material in a heterogeneous environment. With this technique, in simple cases involving small uranium samples introduced into a homogeneous concrete matrix, the detection limits are in the order of a few grams. The current challenge is to improve the detection and localization of material in heterogeneous environments that are realistic in terms of their physical and chemical composition and density.

Subject of the internship

The topic of the internship is to contribute to the development of a Bayesian formalism for processing a set of experimental data (typically delayed photon spectra). Bayesian methods offer two advantages for solving inverse problems. First, they provide relevant results when the number of measurements is small compared to the number of variables involved. Second, they rigorously handle uncertainties and provide results with relevant error bars.

Two approaches are under consideration:

1. Develop an analytical model that predicts the useful signal: Bayesian formalism uses the model to produce estimates and sample the problem's variables. The different stages of signal formation has to be modeled with precision. The output is a mass of nuclear material associated with coordinates.
2. Divide the package into small volumes and calculate a response matrix associating to each element. The measurements are used to invert the matrix and produce as an output the distribution of nuclear material in the inspected volume.

The internship aims to contribute to both approaches. The first focus will be on building surrogate models (meta-models) to predict the photofission rate associated with ^{238}U on the one hand, and detection efficiency on the other hand. These models developed in a simple case (homogeneous matrix) will be tested in a realistic case



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(heterogeneous). The second focus will be on calculating the system response matrix using the models constructed previously. A Bayesian inversion method will be applied in a simple case (homogeneous matrix + known material sample).

To model the configurations of interest, a particle transport code will be used (MCNP6). The output files will be analyzed and the meta-models will be constructed using Python. The Bayesian inversion method will be implemented in Python using the PyMC module.

Depending on the laboratory's schedule and the progress of the internship, participation in additional experiments using the linear accelerator available at the laboratory may be considered.

Skills

Nuclear physics, radiation-matter interactions, data analysis, numerical simulation, and scientific computing. Knowledge of Bayesian inference would be an advantage.

Duration:	9 months		
Profile:	Engineer school or Master 2 (research)		
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References

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- [3] C. Carasco, et al. "Photofission delayed gamma-ray measurements in a large cemented radioactive waste drum during LINAC irradiation". Nuclear Instruments and Methods, A, Vol. 1053, 2023