A Virtual Gamma-ray Spectrum Database for Training in Radioactivity Monitoring

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Introduction

Gamma-ray spectrum analysis is essential for environmental radioactivity monitoring, both for sample measurement or in situ survey. Under elevated count-rate conditions—near hot spots, in highly contaminated samples, random summing produces pile-up structures that distort the measured spectrum [1].

Monte Carlo (MC) codes efficiently generate detector response functions for individual gamma emissions, but they cannot directly reproduce random summing, which is governed by the detector gross count rate and the system's pulse-processing characteristics, not by the source emission rate. Analytical random-summing models exist [2], and virtual spectrum databases for training have been proposed [3]; however, the summing probability depends on the gross count rate that the detector actually sees, which in turn depends on the user-defined radionuclide concentrations of the virtual scenario.

This work integrates an MCNP-based, concentration-normalized response library with a count-rate-driven random-summing model in which x is computed on-the-fly from the user-defined concentrations. The effective resolving time is calibrated against ^{137}Cs irradiation experiments, and the framework generates realistic virtual spectra for training and real-time pile-up diagnostics across measurement environments.

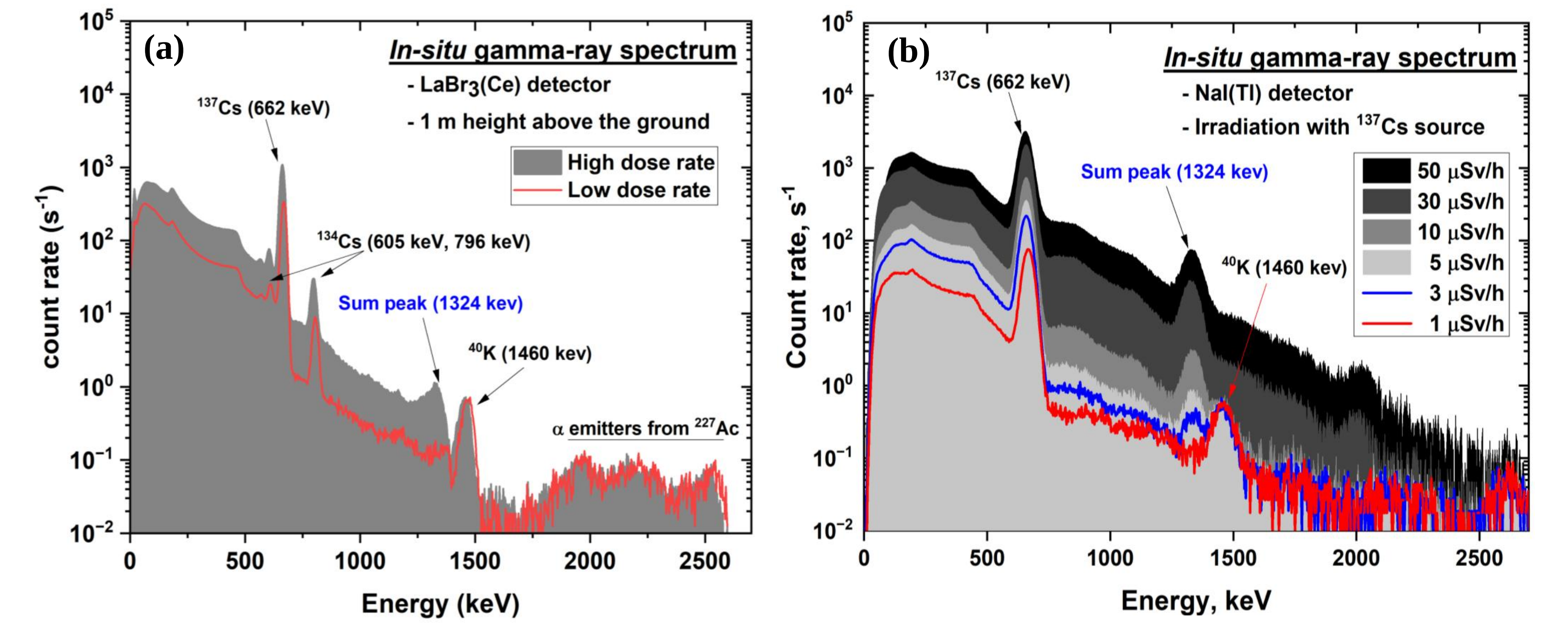


Fig. 1. Gamma-ray spectra exhibiting random-summing peaks under elevated dose-rate conditions: **(a)** field measurement above $^{134/137}$Cs-contaminated soil (LaBr₃(Ce), 1 m height); **(b)** controlled irradiation of a NaI(Tl) detector with a ^{137}Cs source at varying dose rates (1–50 μSv/h)

Material and Methods

Construction of the response spectrum library

- Random summing spectrum model

MCNP6 simulations provide the normalized single-event response per photon $S_{0,i} = S_{0,i,raw}/\varepsilon_{i,total}$, where $S_{0,i,raw}$ is obtained from the F8 pulse-height tally (with Gaussian broadening applied) and $\varepsilon_{i,total}$ denotes the total absolute efficiency. The double-event basis is generated by self-convolution, $S_2 = S_0 \otimes S_0$ assuming independent and identically distributed events for a given source mixture.

Under the assumption that triple- and higher-order pile-up events are negligible, the recorded gamma-ray spectrum is decomposed into single-event and unresolved double-event contributions [2]:

$$S_{RS} = (1-x)S_0 + xS_2 \qquad (1)$$

,where x is the random summing coefficient—i.e., the probability that a recorded trigger represents two events arriving within the system's effective resolving time.

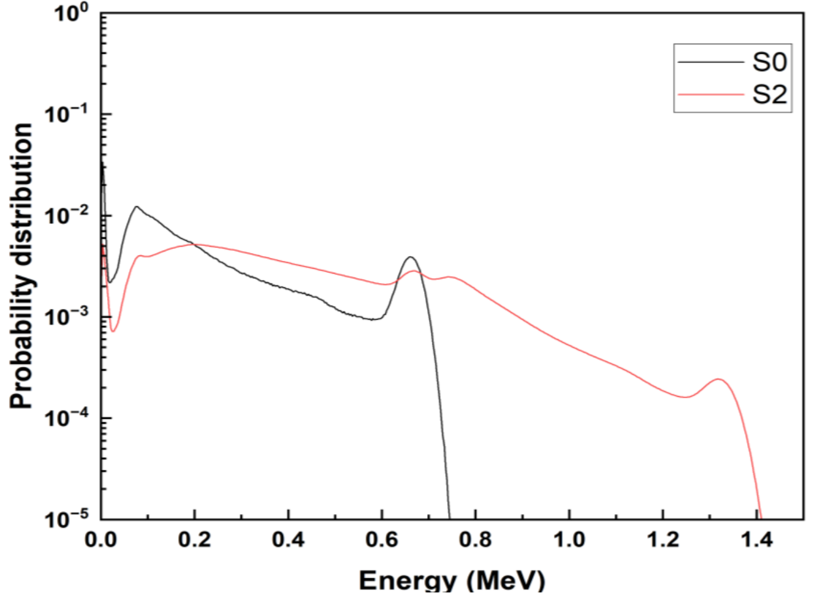


Fig. 2. S_0 spectrum with 661.7 keV γ-ray with MCNP and S_2 spectrum

The response library stores $U_i(E)$, defined as the detector count rate spectrum [cps per Bq/kg], together with the normalized single-event spectrum $S_{0,i}$ and associated metadata. For a given radionuclide mixture, the total single-event spectrum $\sum_i S_{0,i}(E)$ was calculated from the concentration-weighted sum of Ui(E). The double-event basis spectrum $S_{2,total}(E)$ was reconstructed at runtime as:

$$S_{2,total}(E) = S_{0,total}(E) \otimes S_{0,total}(E) \qquad (2)$$

because the random-summing contribution depends on the detector gross count rate, which varies with radionuclide concentration and measurement conditions.

- Conversion from radionuclide concentration to detector count rate

For an input concentration (C_i), the single-event spectrum of radionuclide i was obtained.

$$\boxed{r_{0,i}(E) = C_i \cdot U_i(E)} \Rightarrow \boxed{r_{0,total}(E) = \sum_i r_{0,i}(E)} \Rightarrow \boxed{R_{signal} = \sum_E r_{0,total}(E)} \Rightarrow \boxed{\begin{aligned} &R_{gross} \\ &= R_{bkg} + R_{signal} \end{aligned}}$$

- Estimation of the random summing coefficient

The random summing coefficient (x) was modeled using a Poisson event process:

$$x = 1 - exp(-R_{gross}\tau_{eff}) \qquad (3)$$

,where R_{gross} is detector gross count rate and τ_{eff} is the effective resolving time. Random summing depends on how often two events arrive within the system's resolving time, i.e., on the R_{gross} —the rate at which the detection chain produces triggers, including background and pile-up.

- Determination of the effective time constant from experiments (Fig.1(b))

The double-event scaling coefficient was determined from ^{137}Cs irradiation spectra. Using ^{137}Cs irradiation spectra measured at different dose-rate condition, the ratio of the random summing peak was evaluated as:

$$R_{exp} = \frac{N_{1324}}{N_{662}}$$

The model spectrum was generated with candidate x:

$$S_{model}(x) = (1-x)S_0 + xS_2 \qquad (4)$$

,where optimal x was selected by minimizing:

$$error(x) = \left[R_{model}(x) - R_{exp}\right]^2 \qquad (5)$$

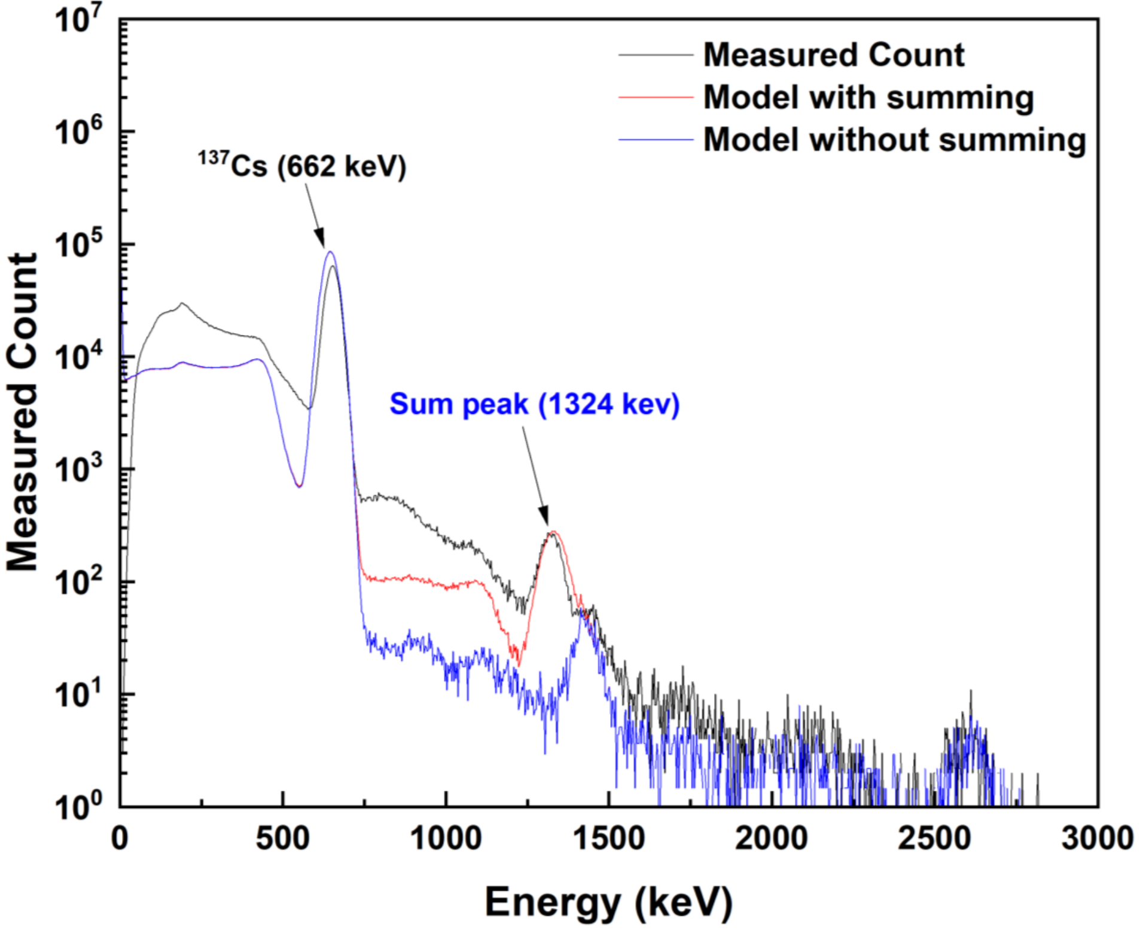


Fig. 3. Comparison of measured spectrum and virtual spectra for validation of the random-summing model.

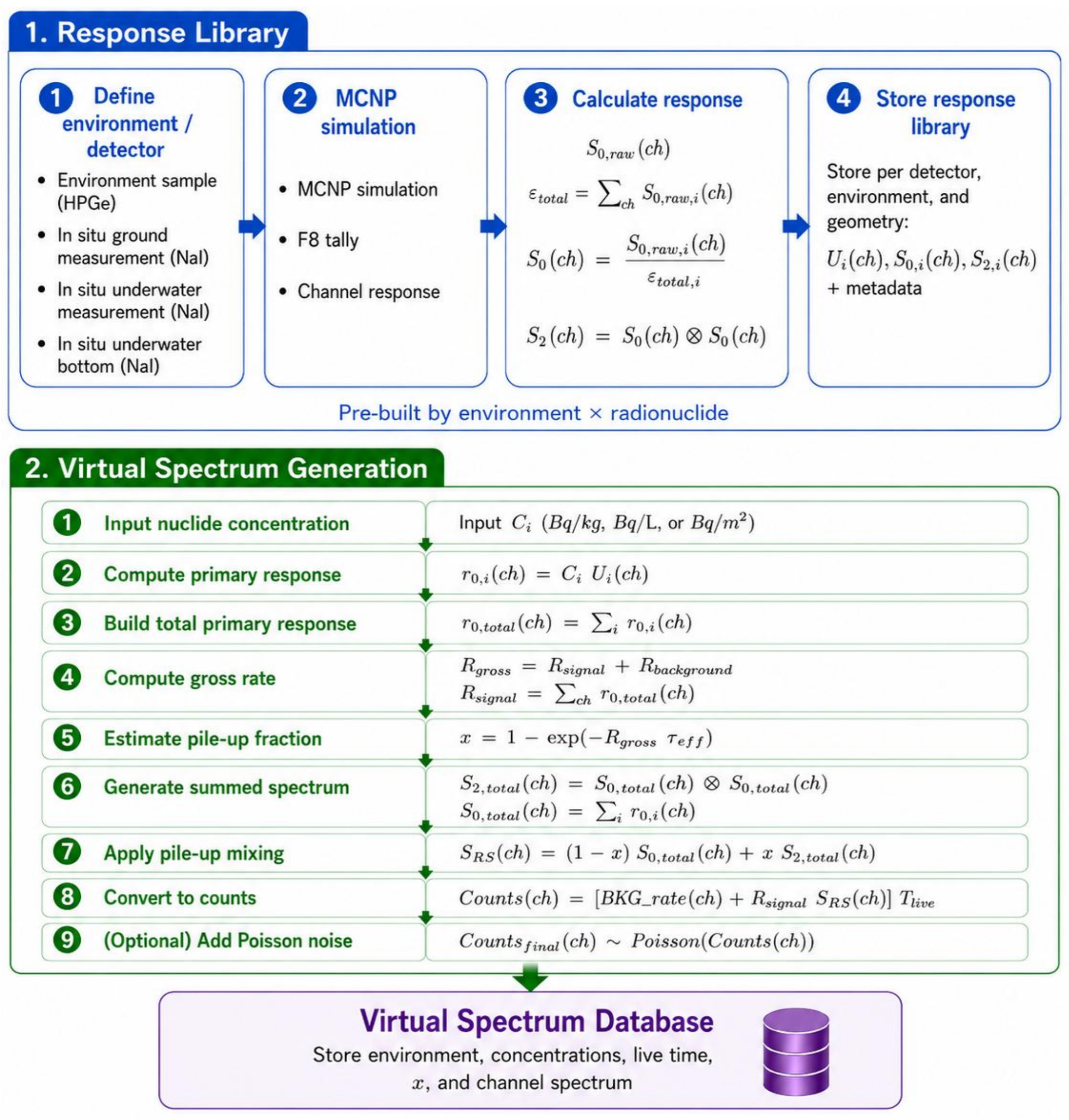
The effective resolving time was $\tau_{eff} \approx 0.18\,\mu s$. The model including random summing (x=0.00905) reproduces the additional summed-event contribution around the 1324 keV region, which is not represented by the single-event model.

Results

Generation of Virtual Gamma Spectrum Database

- A MCNP6 based response library was constructed for each measurement environment and radionuclide.
- User-defined radionuclide concentrations are directly converted into count-rate spectra using unit concentration responses.
- The detector gross count rate is calculated from the generated single-event spectrum.
- The random summing coefficient is automatically determined as Eq.(3).
- The final virtual spectrum is generated as:

$$N_{virtual} = BKG + \sum C_i \cdot U_i \cdot S(x) \cdot time \qquad (6)$$


1. Response Library

① Define environment / detector
- Environment sample (HPGe)
- In situ ground measurement (NaI)
- In situ underwater measurement (NaI)
- In situ underwater bottom (NaI)

② MCNP simulation
- MCNP simulation
- F8 tally
- Channel response

③ Calculate response

$S_{0,raw}(ch)$

$\varepsilon_{total} = \sum_{ch} S_{0,raw,i}(ch)$

$S_0(ch) = \frac{S_{0,raw,i}(ch)}{\varepsilon_{total,i}}$

$S_2(ch) = S_0(ch) \otimes S_0(ch)$

④ Store response library

Store per detector, environment, and geometry:

$U_i(ch), S_{0,i}(ch), S_{2,i}(ch)$ + metadata

Pre-built by environment × radionuclide

2. Virtual Spectrum Generation

① Input nuclide concentration	Input C_i $(Bq/kg,\ Bq/L,$ or $Bq/m^2)$
② Compute primary response	$r_{0,i}(ch) = C_i\ U_i(ch)$
③ Build total primary response	$r_{0,total}(ch) = \sum_i r_{0,i}(ch)$
④ Compute gross rate	$R_{gross} = R_{signal} + R_{background}$ $R_{signal} = \sum_{ch} r_{0,total}(ch)$
⑤ Estimate pile-up fraction	$x = 1 - \exp(-R_{gross}\ \tau_{eff})$
⑥ Generate summed spectrum	$S_{2,total}(ch) = S_{0,total}(ch) \otimes S_{0,total}(ch)$ $S_{0,total}(ch) = \sum_i r_{0,i}(ch)$
⑦ Apply pile-up mixing	$S_{RS}(ch) = (1-x)\ S_{0,total}(ch) + x\ S_{2,total}(ch)$
⑧ Convert to counts	$Counts(ch) = [BKG\_rate(ch) + R_{signal}\ S_{RS}(ch)]\ T_{live}$
⑨ (Optional) Add Poisson noise	$Counts_{final}(ch) \sim Poisson(Counts(ch))$

Virtual Spectrum Database
Store environment, concentrations, live time, x, and channel spectrum

Fig. 4. Frameworks for generation of real-time virtual γ-spectrum DB

Discussion & limitation

- Generates expected spectra for real-time comparison with measured spectra.
- Support real-time pile-up and high count rate diagnostics.
- Focuses on random summing from temporally overlapped independent events.
- Cascade-related true coincidence summing may also affect spectra for multi-gamma emitters and decay-series radionuclides.

Conclusion

- Generated realistic spectra by combining radionuclide concentration, detector response, background, live time, and counting statistics.
- Supports real-time comparison between predicted and measured spectra for high-count-rate diagnostics.
- Future work will extend the framework to a GPS-based environmental radiation monitoring training platform

References

[1] T. Nemeš, D. Mrdja, and I. Bikit, "Generalized equation for the sum-peak method, accounting for random coincidences," Nucl. Instrum. Methods Phys. Res. A, vol. 898, pp. 11–17, Aug. 2018, doi: 10.1016/j.nima.2018.04.042.
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[3] Y. Choi, Y.-Y. Ji, and S. Joo, "Database of virtual spectrum of artificial radionuclides for education and training in in-situ gamma spectrometry," Nucl. Eng. Technol., 2023, doi: 10.1016/j.net.2022.07.022.

Acknowledgements

This research was funded by the Ministry of Oceans and Fisheries, grant number RS-2024-00406249.

IEEE REAL TIME CONFERENCE 2026