Deep Learning-Based Multi-Isotope Identification for Portable Low-Resolution Gamma-Ray Detectors Using 1D Convolutional Neural Networks

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Motivation and objective

Portable NaI(Tl) gamma spectrometers are practical for rapid field deployment, but isotope identification becomes difficult when spectra contain overlapping photopeaks, environmental background and limited counting statistics. This work reformulates isotope identification as a **multi-label** problem, allowing several radionuclides to be reported from one mixed spectrum.

Objective

Develop a compact 1D convolutional neural network that ranks and identifies radionuclides in portable gamma spectra for on-scene nuclear security and radiological forensics.

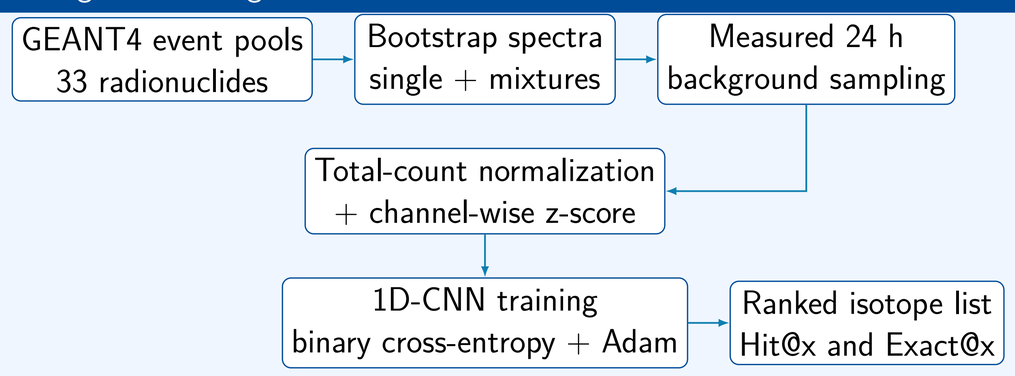
Dataset synthesis for realistic mixed spectra

- **Detector model:** portable 3 in. $\times$ 3 in. NaI(Tl) spectroscopic detector.
- **Input spectra:** 1024 channels covering the 0–3 MeV energy range.
- **Classes:** 33 radionuclides plus a background-only class, giving 34 sigmoid outputs.
- **Mixtures:** single-isotope spectra and predefined 2-, 3- and 4-isotope combinations.
- **Acquisition variability:** source counts from 5×10^3 to 10^5 and signal fraction from 0.1 to 1.0.
- **Background:** random events sampled from a measured 24 h environmental background spectrum.
- **Mixture ratios:** randomly assigned in the range 0.1–0.9 and normalized to sum to unity.

Table: Radioisotopes used in this study, grouped by primary application. Some radionuclides may be relevant to more than one application category; the table is grouped by primary application. The dataset includes 33 unique radionuclides and one background-only class.

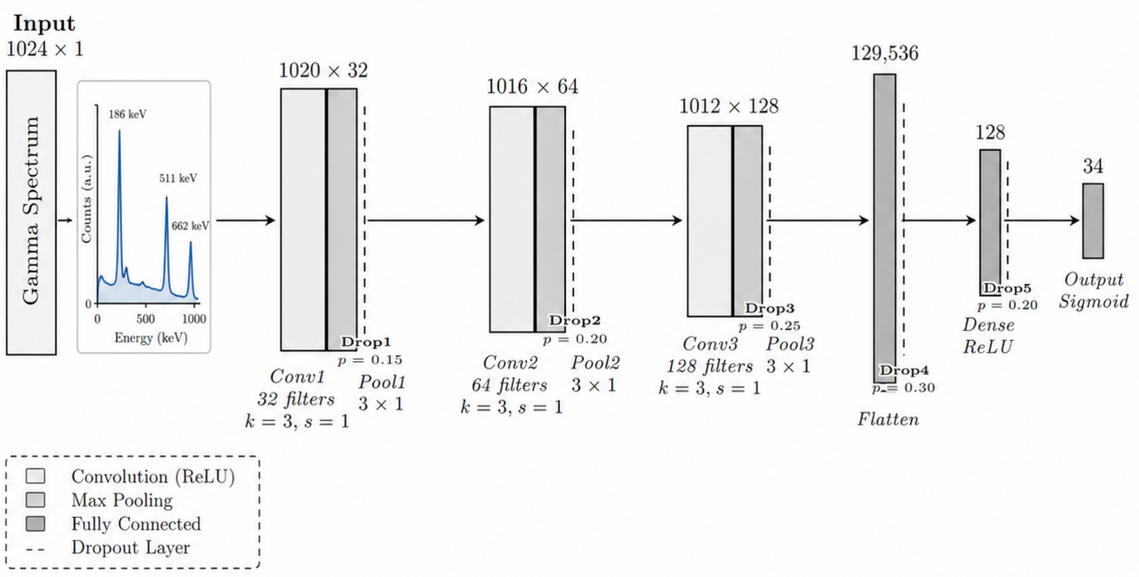
Category	Isotopes
Special Nuclear Material (SNM)	^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu
Other nuclear materials / fuel-cycle	^{237}Np, ^{232}Th
Medical (diagnostic / therapeutic)	^{99m}Tc, ^{123}I, ^{131}I, ^{111}In, ^{67}Ga, ^{201}Tl, ^{133}Xe, ^{177}Lu, ^{153}Sm, ^{89}Sr, ^{51}Cr, ^{99}Mo
Industrial	^{192}Ir, ^{75}Se, ^{60}Co, ^{137}Cs, ^{241}Am
Calibration / QA standards	^{133}Ba, ^{57}Co, ^{152}Eu, ^{22}Na, ^{137}Cs, ^{54}Mn, ^{109}Cd, ^{204}Tl
Natural background (NORM / environmental)	^{40}K, ^{226}Ra, ^{232}Th
Additional class	Background

Preprocessing and training workflow



Preprocessing statistics were calculated on the training partition only and then applied unchanged to the validation and test sets, avoiding information leakage.

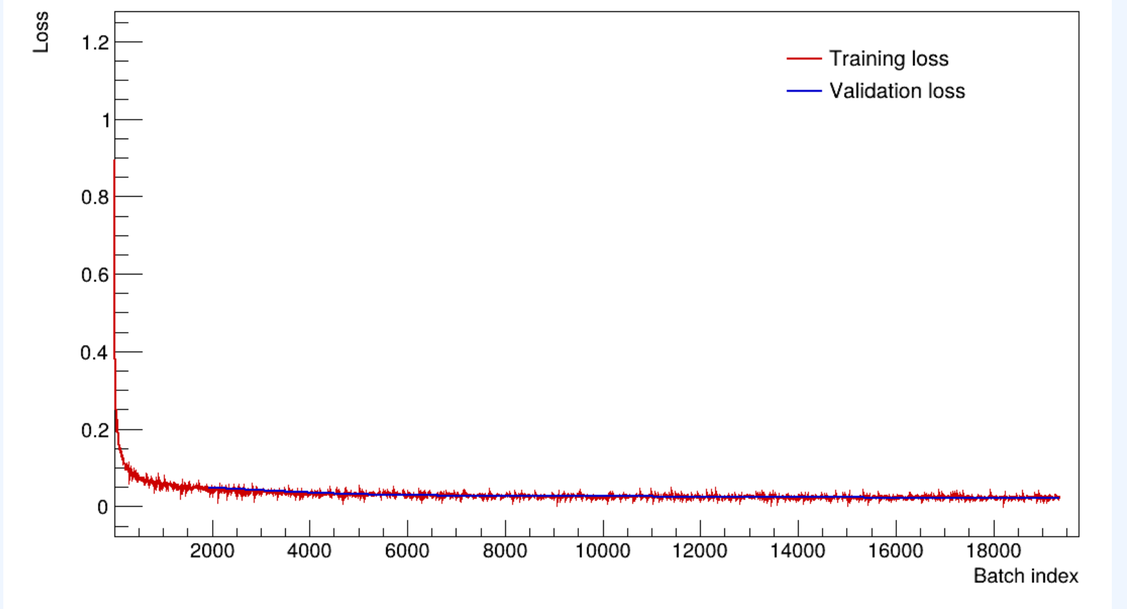
Multi-label CNN architecture



Layer	Output Size	Layer Type	Parameters
Input	1024×1	—	—
Conv1 + Pool1 + Drop1	1020×32	Conv + Pool + Dropout	320
Conv2 + Pool2 + Drop2	1016×64	Conv + Pool + Dropout	6,208
Conv3 + Pool3 + Drop3	1012×128	Conv + Pool + Dropout	24,704
Flatten + Drop4	129,536	Flatten + Dropout	0
Dense (ReLU) + Drop5	128	Fully Connected + Dropout	16,581,536
Output (Sigmoid)	34	Fully Connected (Sigmoid)	4,386
Total Trainable Parameters			**16,617,154**

The network uses three Conv1D–MaxPool–Dropout blocks for local spectral feature extraction, a 128-neuron dense layer for global feature integration and a 34-neuron sigmoid output layer for independent isotope probabilities.

Training behavior



Training and validation losses decrease rapidly and then stabilize at low values. Their close agreement indicates stable learning, with no visible generalization gap or evidence of overfitting.

Evaluation metrics

- **Hit@x:** equals 1 when at least one true isotope appears within the top-x predictions.
- **Exact@x:** equals 1 when the complete true isotope set is contained within the top-x predictions.

Interpretation

Hit@x supports rapid field triage by checking whether the ranked list contains a correct radionuclide. Exact@x is stricter and tests full mixture recovery.

Key identification performance

Spectrum type	Ranking metric	Value
2-isotope mixtures	Hit@1	1.000
2-isotope mixtures	Exact@2	0.986
3-isotope mixtures	Hit@1	1.000
3-isotope mixtures	Exact@3	0.986
4-isotope mixtures	Hit@1	1.000
4-isotope mixtures	Exact@4	0.979

1.000
Hit@1 for 3-isotope mixtures

0.986
Exact@3 full recovery

34
network output classes

16.6M
trainable parameters

What this study adds

- Extends previous single-isotope CNN [1] identification to **mixed gamma spectra**.
- Uses a **sigmoid multi-label output**, rather than a mutually exclusive softmax classifier.
- Trains on realistic GEANT4 [4] based spectra with measured background, variable count statistics and randomized isotope ratios.
- Demonstrates high full-set recovery for 3-isotope mixtures with a portable medium-resolution detector model.

Operational relevance

- Provides a short ranked candidate list for rapid on-scene decision support.
- Helps address peak overlap and weak-component masking in mixed-source scenarios.
- Supports nuclear security and radiological crime scene investigations using deployable instrumentation.
- Experimental validation with measured mixed spectra is the next development step.

Conclusions

- A compact 1D-CNN can recover multi-isotope composition in simulated portable NaI(Tl) spectra.
- Realistic data generation is central: measured background, source/background variability and randomized mixture fractions improve robustness.
- The method provides a scalable basis for confidence-aware reporting, isotope-family grouping and future mixture-unmixing approaches.

QR code and references

http://karafasoulis.eu

Selected references

1. K. Karafasoulis et al., JINST 20 (2025) C12027.
2. M. Kamuda et al., Nucl. Instrum. Meth. A 954 (2020) 161385.
3. G. Daniel et al., IEEE Trans. Nucl. Sci. 67 (2020) 644–653.
4. S. Agostinelli et al., GEANT4, Nucl. Instrum. Meth. A 506 (2003) 250–303.

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Application: radiological crime scene investigations

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