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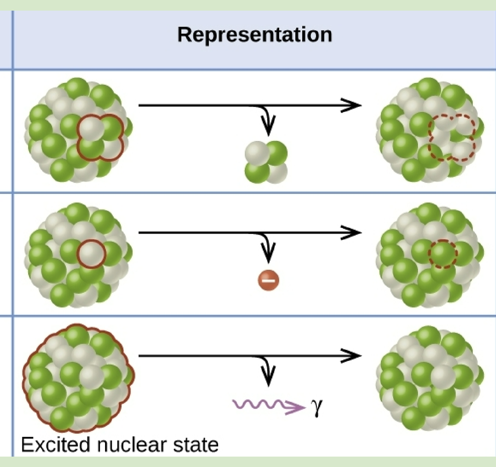
Probabilistic Radioisotope Identification (PrRIID) Using List-Mode Gamma Ray Measurements

Abstract: Radioisotope identification (RIID) is typically performed using gamma-ray spectroscopy, essentially comparing energy spectra against known templates. However, the physics of radioactive decay is completely understood, and nuclear decays follow well-defined decay chains with known branching probabilities and mean decay times. Machine learning techniques processing pulse-by-pulse (list-mode) data from a gamma ray detector could take advantage of temporal and sequential correlations in the data to make a quicker real-time inference than is possible with the spectrum alone. In principle, by avoiding the information loss arising from binning list-mode data, a probabilistic, temporal radioisotope identification algorithm could perform inference with higher confidence and/or higher accuracy than existing methods.

A Nuclear Physics Primer

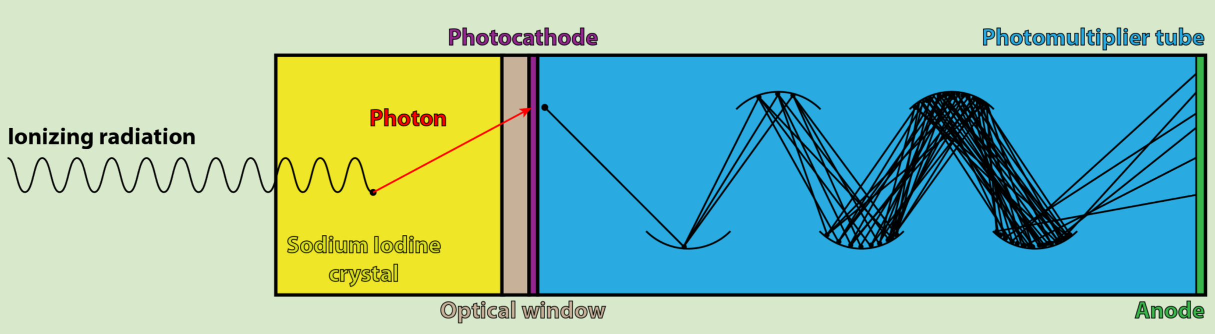
Types of Nuclear Decay

Nuclear decay is the process by which unstable nuclei lose energy by radiation. Individual decays occur at random times, but collectively there are well-documented branching probabilities and mean decay times, which can be modeled by a Poisson process. Gamma decay is the mode of decay whose emissions travel the farthest, and is often used to infer the isotopes present in a decaying sample.

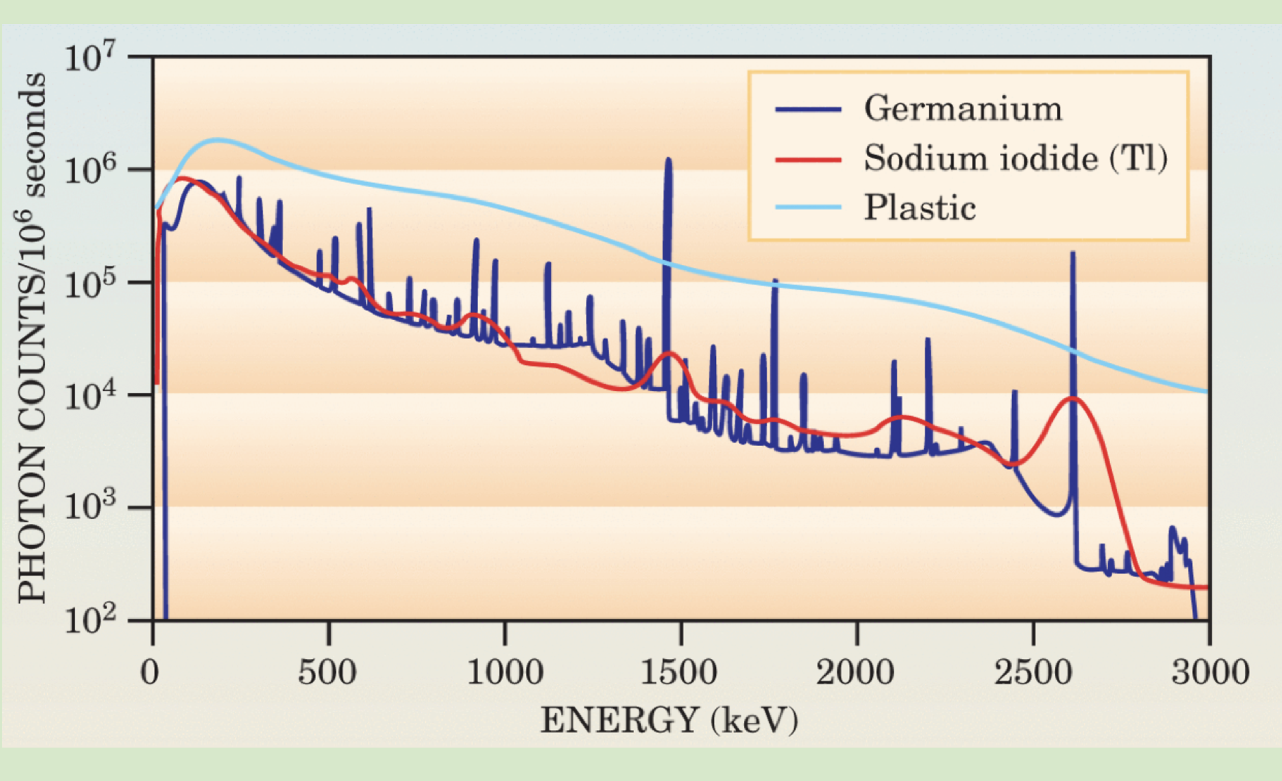
Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	${}^{A}_{Z}X \quad {}^{4}_{2}He + {}^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	${}^{A}_{Z}X \quad {}^{0}_{-1}e + {}^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	${}^{A}_{Z}X \quad {}^{0}_{0}\gamma + {}^{A}_{Z}Y$		A: unchanged Z: unchanged

https://chem.libretexts.org/Courses/Oregon_Institute_of_Technology/OIT%3A_CHE_201_-_General_Chemistry_I_(Anthony_and_Clark)/Unit_3%3A_Nuclei_Ions_and_Molecules/3.1%3A_Nuclear_Chemistry_and_Radioactive_Decay

Gamma Ray Detection

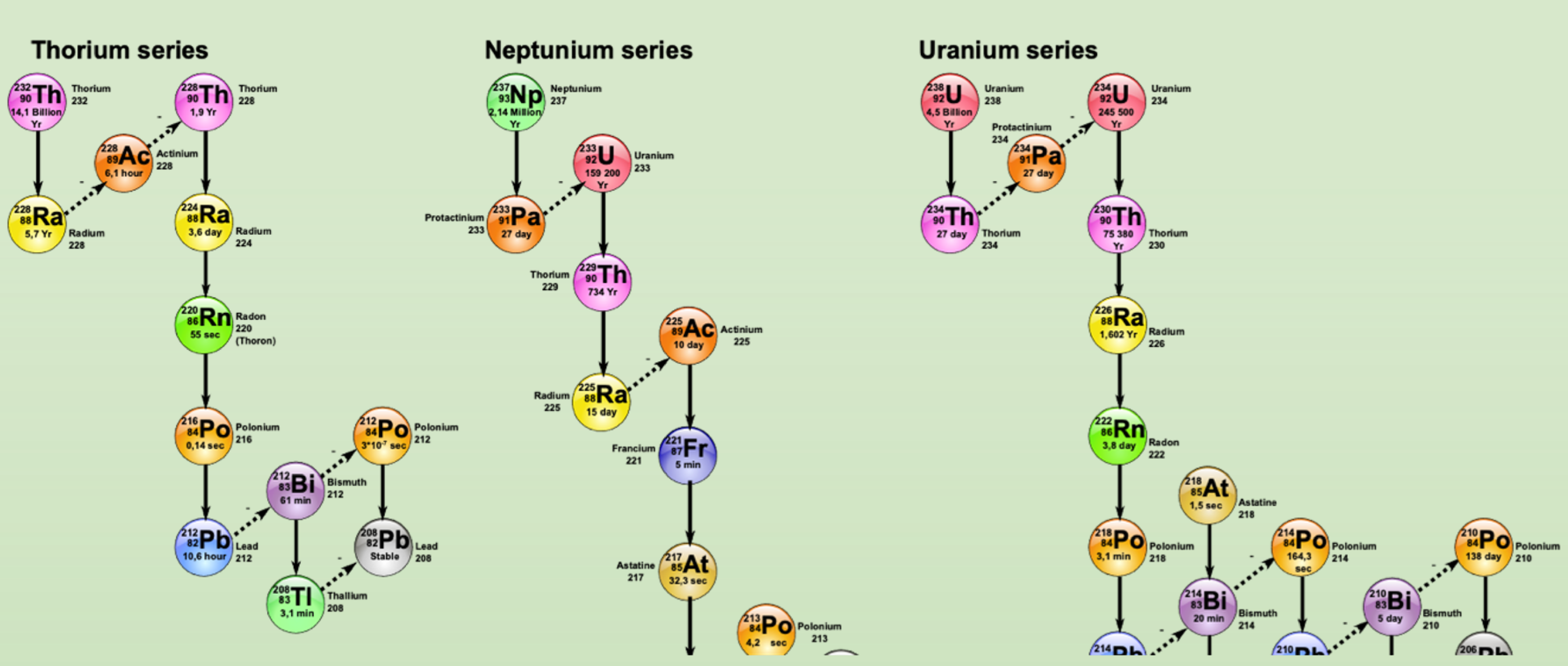


A scintillation detector is one methods of detecting gamma rays. A high-energy photon strikes a scintillator, which re-emits energy in a visible or near-visible portion of the spectrum. The lower-energy photons are converted to electrons by a photocathode, and the electronic signal is amplified in a photomultiplier tube. Pulses are collected over time to form an energy spectrum such as the one shown below. The plot compares the shapes of spectra collected using various detector types.



https://physicstoday.scitation.org/doi/10.1063/1.1839375

Nuclear Decay Series

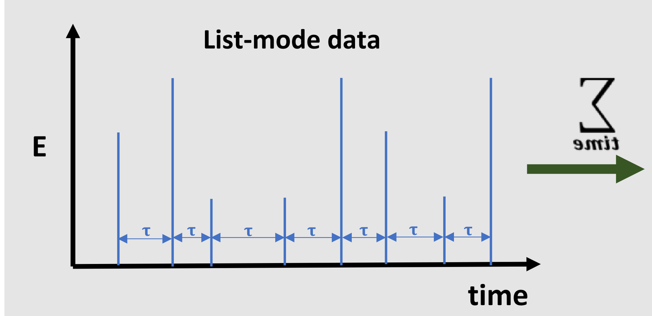


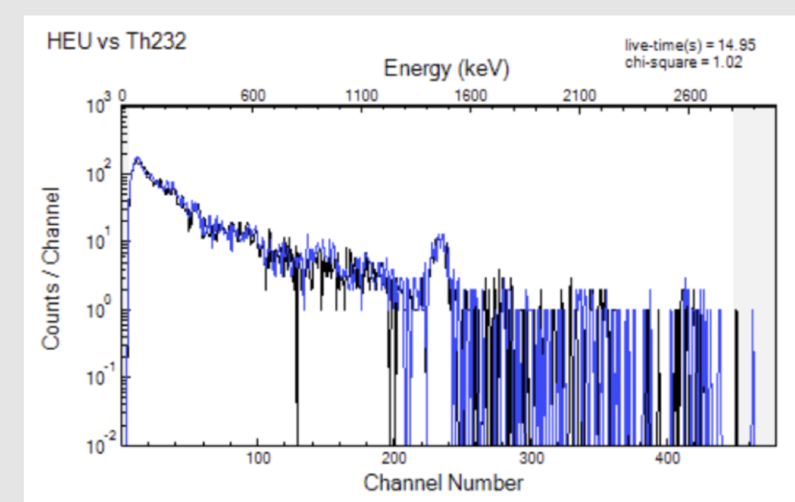
State of the Art of RIID

Gamma Ray Spectrum Template-Matching

Currently, gamma ray energy spectra are used to identify isotopes, generally by comparison of the spectrum to a template. However, at low signal levels, there can be insufficient information in the spectrum to distinguish isotopes. This is where a technique also incorporating time-of-arrival information would show an advantage.

The signal directly from the detector is a series of pulses in time, and is called *list-mode*. The pulse heights are the gamma ray energies. The inter-pulse timing, and the sequence of pulses, contain information that a probabilistic machine learning model could utilize.





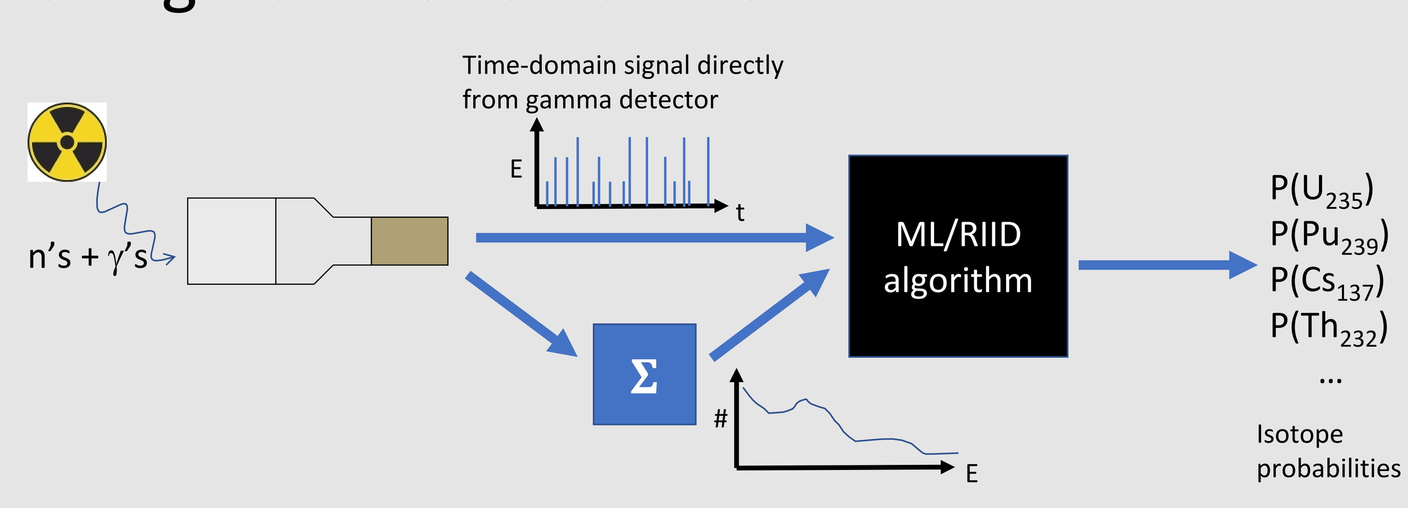
In the example above, spectra of highly enriched uranium (HEU, shown in blue) and thorium-232 (shown in black) are both plotted. They are currently indistinguishable, but they could be differentiated by considering the inter-pulse times.

Practical Scenarios

Mobile radiation detectors such as the one in this Thermo Fisher PackEye Radiation Detection Backpack are often used to ensure public safety at large events. In this scenario, it can be difficult to discern malicious sources or radiation from benign ones, due to weak signals and moving sources.

https://www.thermofisher.com/order/catalog/product/FHT1377

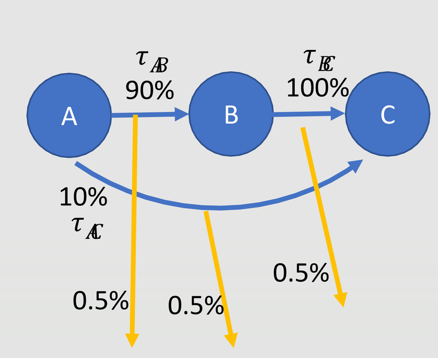
Using List-Mode Data for RIID



Using temporal & sequential gamma ray data:

- Limits of detection could be lowered
- More confidence could be assigned to measurements
- Correlated phenomena could be combined (gamma + neutron)

Probabilistic Methods Being Developed



1. Hidden Markov models
2. Statistical methods
3. Recurrent neural networks

Transition matrix, **A**

	A	B	C
A	0	0	0
B	0.9	0	0
C	0.1	1	0

Rate matrix, **T**

	A	B	C
A	0	0	0
B	τ_{AB}	0	0
C	τ_{AC}	τ_{BC}	0

Observation ("emission") matrix, **E**

	A	B	C
A	0	0	0
B	0.005	0.005	0.005
C	0.5	0.5	0

References

McDonald, Joseph C., Bert Coursey, and Michael Carter. "Detecting illicit radioactive sources." *Physics Today* 57.PNNL-SA-42028 (2004). https://doi.org/10.1063/1.1839375

M. Halász and M. Szieberth, "Markov chain models of nuclear transmutation: Part I – Theory," *Annals of Nuclear Energy*, vol. 121, pp. 429-445, 2018/11/01/ 2018, doi: https://doi.org/10.1016/j.anucene.2018.07.010.

E. Clarkson and M. Kupinski, "Quantifying the loss of information from binning list-mode data," *J. Opt. Soc. Am. A*, vol. 37, no. 3, pp. 450-457, 2020/03/01 2020, doi: 10.1364/JOSAA.375317.

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NNSA National Nuclear Security Administration

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