Radiation Transport: A Simulation and Analysis Project with the Pacific Northwest National Laboratory

Seth Garcia, Petar Grigorov, Brittney Marzen
Embry-Riddle Aeronautical University

Background and Purpose

Radiation is defined as the transportation of energy in the form of waves or particles. It is emitted by unstable isotopes of elements from the periodic table. For example, the elements Cobalt-60 and Cesium-137 undergo radioactive decay of type beta, meaning that they emits beta particles (i.e. electrons) to become stable. On the other hand Technetium-99 undergoes gamma-decay, which emits photons [1].

Radiation from unstable sources can be measured using detectors that count the number of particles emitted by them. Note that different types of particles have different energies. These measurements, also known as radiation energy spectra (as seen in *Fig. 1*), are unique for each source of radiation. The sources are identified based on the distinct locations and sizes of the peaks in the graphs. In realistic applications, a background radiation spectrum will feature signals from many sources of radiation. The mixing of signals will make individual ones harder to distinguish. They can be separated with the help of computational tools. For example *Fig. 1* shows a cleanly separated signal for two sources of radiation that can be clearly determined by looking at the peaks.

For this research project, mathematical and computational methods for Reduced Order Modelling (R.O.M.) are employed to separate the mixed signals with the goal of identifying individual radiation sources and their locations [1]. Simulated data from three radioactive sources provided by the Pacific Northwest National Laboratory (PNNL) are used in this project: Cobalt-60, Cesium-137, Technetium-99.

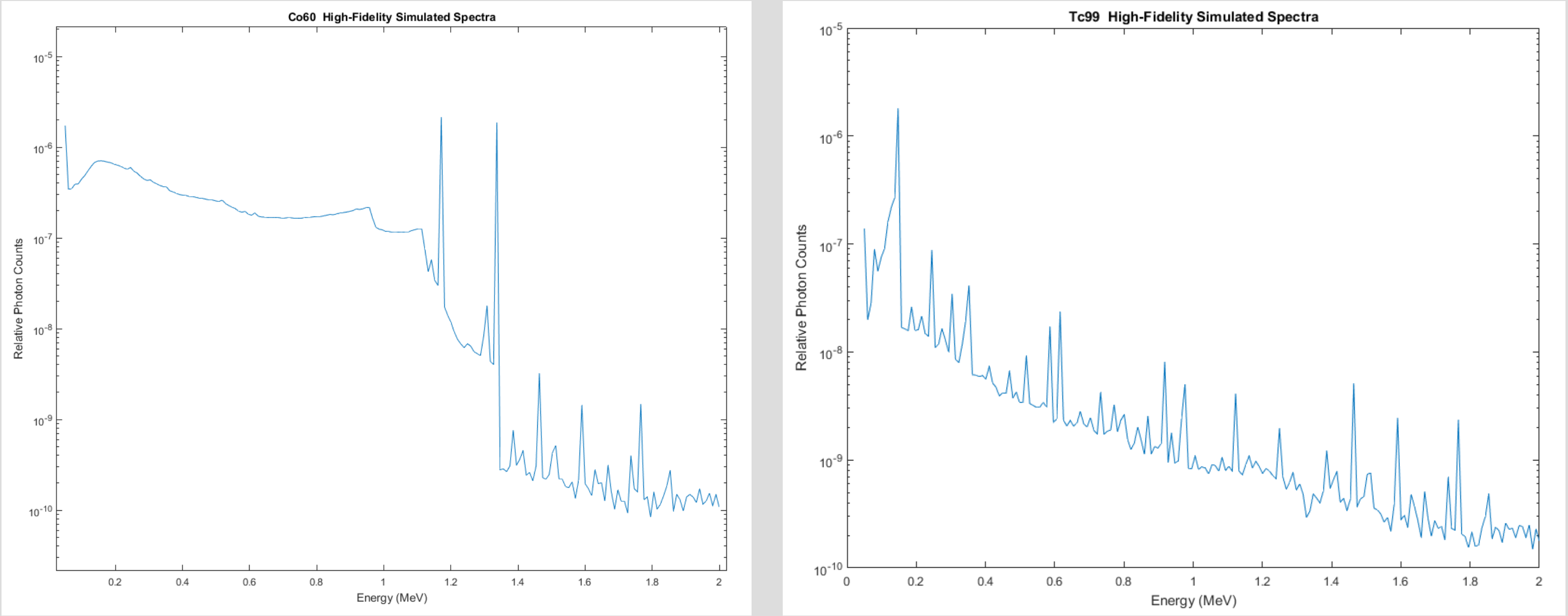

Figure 1: Radiation energy graphs with a clean signal and distinguishable peaks for Cobalt-60 (left) and Technetium-99 (right)

Methods and Goals

- Three techniques of R.O.M. are explored: Principal Component Analysis (PCA), Non-Negative Matrix Factorization (NNMF), and CP Tensor Decomposition (CPT).
- Principal Component Analysis identifies the most relevant directions of variance in the data. PCA converts a correlated data set of many dimensions into a simpler data set of linearly uncorrelated variables called principal components. Ranked by variance, the first principal component has the highest variance, the second principal component has the second highest, and so on until all principal components are extracted. PCA can capture the most important features of the data without much loss of information by reducing dimensions of the data.
- Non-Negative Matrix Factorization works similarly like PCA in its ability to decompose data of many variables by creating a user-defined number of features. To perform NNMF the data (organized in a matrix) is decomposed into two matrices of lower rank, whose product will be approximated to the original matrix. Unlike PCA however, all features (eigenvectors) in NNMF have non-negative coefficients and are the linear combination of the original data set.
- CP Tensor Decomposition factorizes a multidimensional tensor that contains the simulated data into a sum of products of tensor vectors. The product of all three tensor vectors are approximately equal to the original data tensor.
- The results from each method will be compared and analyzed for determining which R.O.M. is best suited in identifying and locating sources of radiation.

Research Tasks & Questions

- Use MATLAB code to perform three types of R.O.M. (PCA, NNMF, CPT) that decompose the data into separate features
- Compare features from the three R.O.M. methods and determine which one is best suited for identifying radiation sources.
- Qualitatively determine the pros and cons of each method.
- What are useful metrics for comparing the features computed by the three methods?
- Do the different data decomposition approaches result in the same features?
- If new simulations are given, can ROM be used to tell what and where the new source is?

Data Description

The simulated data provided by the PNNL contains a total of four 4-D arrays: one for each radioactive source (Co-60, Cs-137, Tc-99) and one for the radiation background. Each 4-D array is of size 2x201x21x21. The first dimension contains the two variables x and y in a spectral graph as shown in *Figure 1*. The x-axis represents the energies of detected particle while the y-axis represents the relative count of particles for each energy value. The second dimension contains 201 columns that are called "energy bins". Each energy bin corresponds to the number of photons that have been detected at a certain energy level.

The radioactive background is observed from more than one location, so the third and fourth dimensions represent a square array of 21x21 detectors (441 detectors in total). A distinct radiation energy spectrum can be created for each detector.

PCA Results

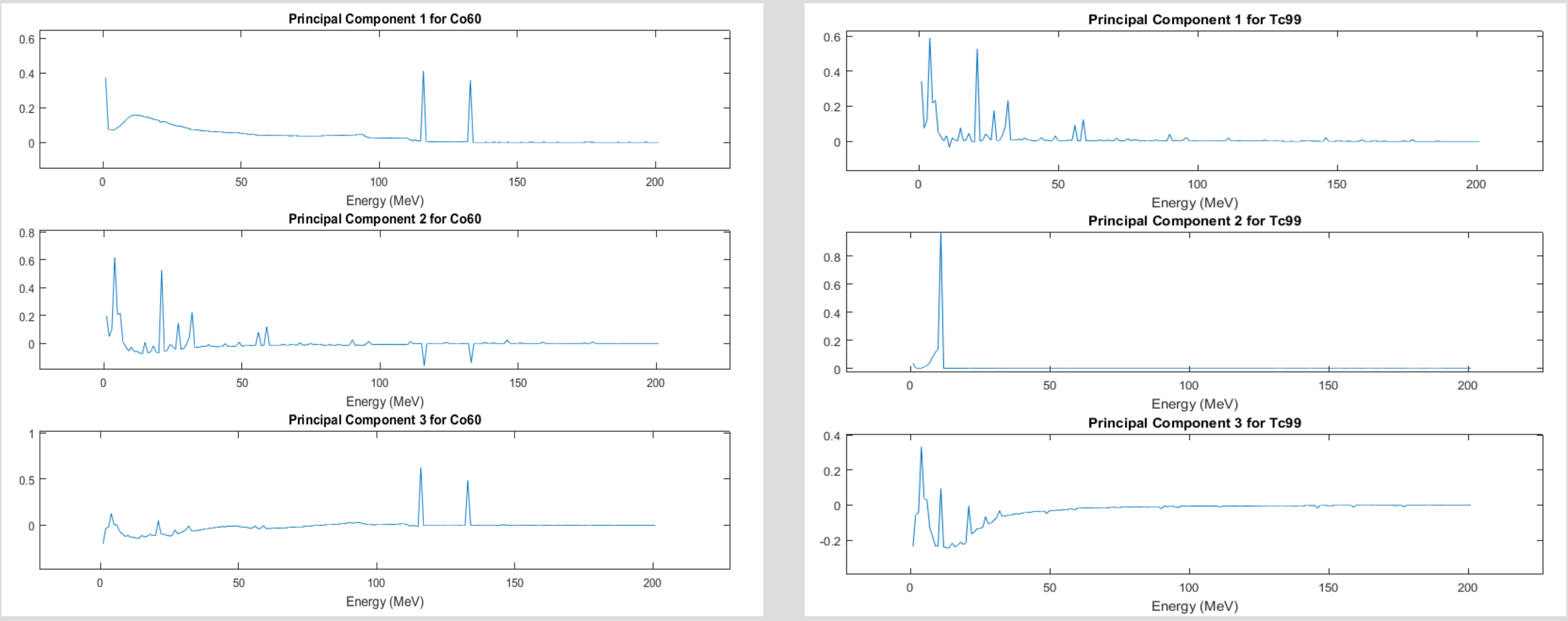

Figure 2: Resulting radiation energy spectra using PCA. The first three principal components are shown for Cobalt-60 (left) and Technetium-99 (right).

- The principal components show the more prominent emission peaks in the decomposition of data for each source of radiation.
- Results for Co-60 and Tc-99 in *Fig. 2* show two major emission peaks in the first principal component.
- In the second principal component the smaller variations within the data produce smaller peaks that are not as prominent as in the first principal component, but still contain important aspects of the data.
- The third principal component shows even less variation of the data, but its peaks are still prominent enough to be considered in the analysis.
- The PCA algorithm can show as many principal components as desired, but for most applications only the first few are necessary for accurate analysis.

NNMF Results

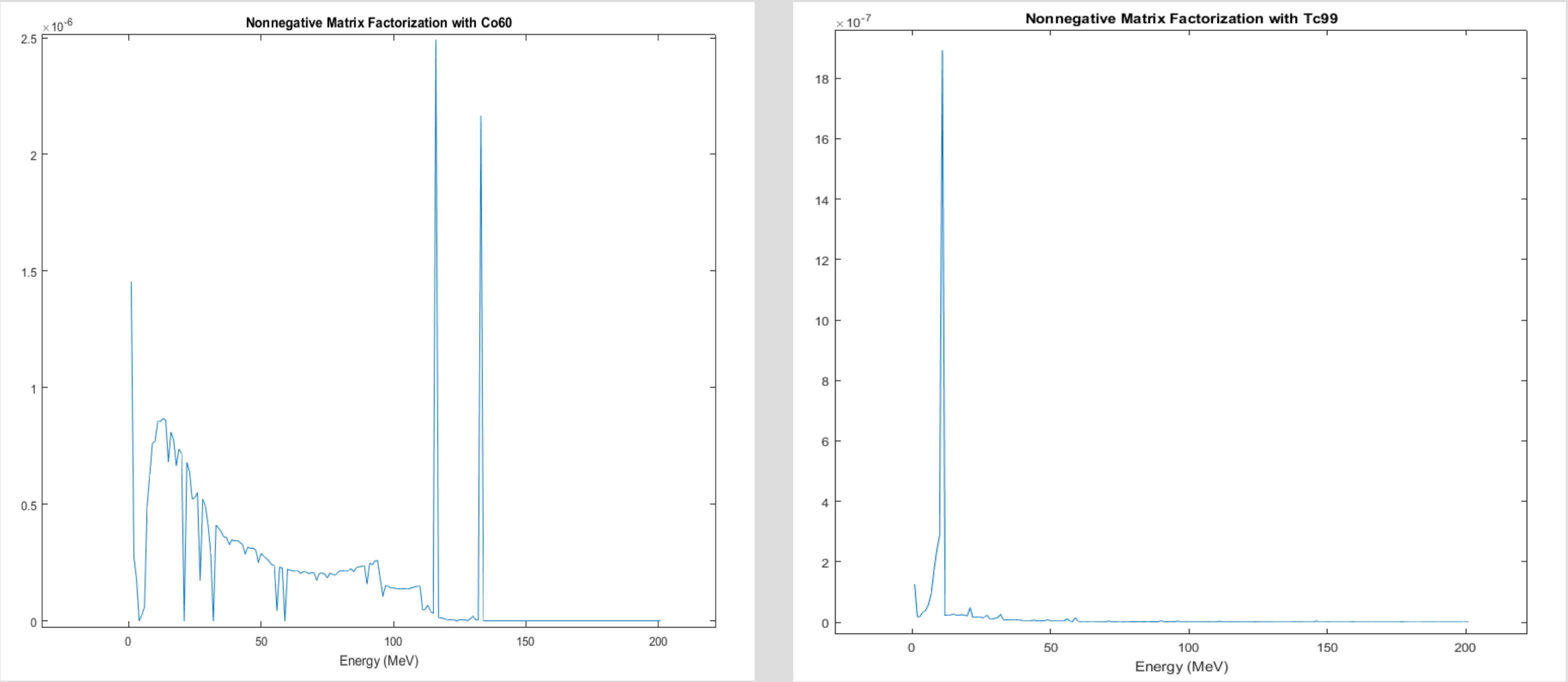

Figure 3: Resulting radiation energy spectra using NNMF for Cobalt-60 (left) and Technetium-99 (right).

- The NNMF algorithm places all relevant radiation emission peaks in a single graph, compared to PCA which splits and ranks them according to variance.
- The Nonnegative Matrix Factorization algorithm returns nonnegative results (hence the name), as shown in *Fig. 3*.
- The NNMF results in Fig. 3 reveal the same peaks that have been observed using PCA for both Co-60 and Tc-99.

Key Findings

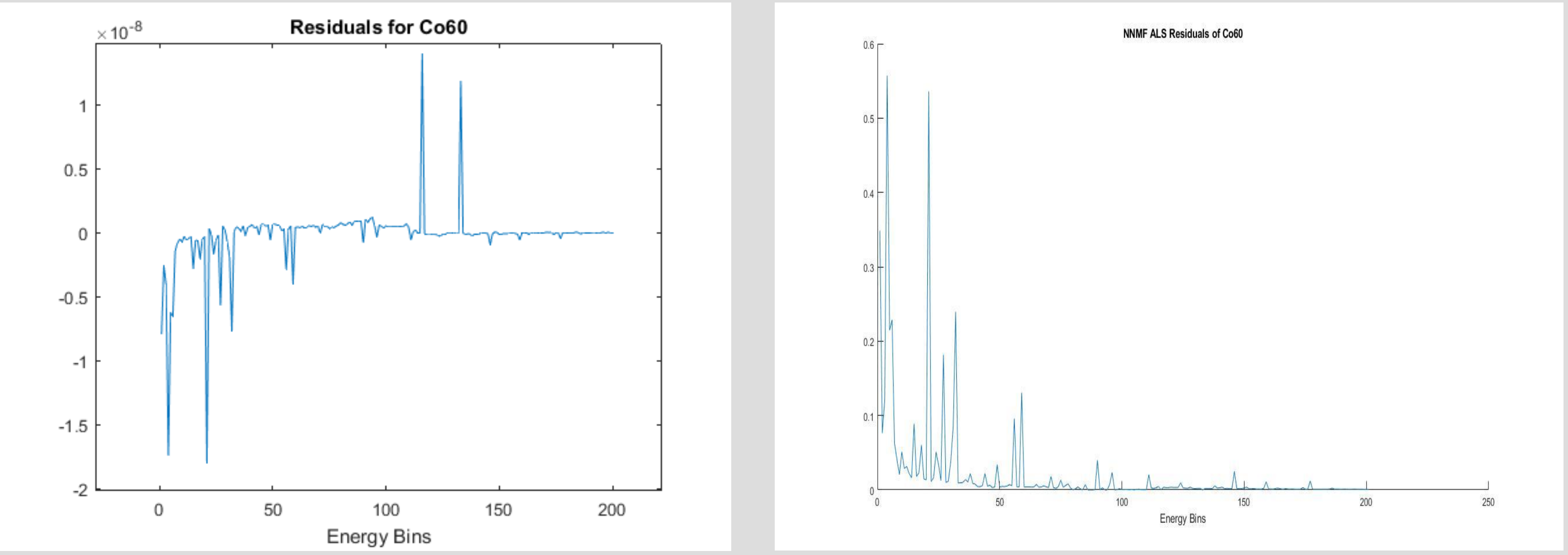

Figure 4: Residuals for Cobalt-60 using PCA are show on the left. Residuals for Cobalt-60 using NNMF are shown on the right

- The main comparison between the results from PCA and NNMF is how the major peaks are displayed, as shown in Fig. 4. The emission peaks are important reference points to be looking for in the other decomposition methods such as CP Tensor Decomposition (CPT).
- The advantage of performing PCA over NNMF is that after data decomposition is performed, the results are ordered based on variations within the data. In contrast, the absence of ranking in NNMF makes it more challenging to extract important information because all of it is shown on a single graph.

References

[1] Udagedara, Indika, et al. "Reduced Order Modeling for Accelerated Monte Carlo Simulations in Radiation Transport." *Applied Mathematics and Computation*, vol. 267, 2015, pp. 237–251.