Ohio State College of Engineering MS/PhD/Candidacy Dissertation Template

Dissertation

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Firstname Midname Lastname, B.S., M.S.

Graduate Program in Nuclear Engineering

The Ohio State University

2023

Dissertation Committee:

Richard Vasques, Advisor

Someone 1, Co-Advisor

Someone 2

Maybe Someone 3

Abstract

This is your abstract. Fill it accordingly.

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Dedicated to elevators for always lifting people up and being helpful on so many levels.

Acknowledgments

I thank my friends and family, without whom this work would have been completed two years earlier.

In reality, this is the only page of the dissertation of which the author has full control. You can write anything you want here, and no one can tell you it is wrong (except if the margins don't line up!!!!).

Vita

August 2016	B.S. in something, The Ohio State University
Some date	Some degree, Some place
September 2016 to present	Graduate Research Associate, The Ohio State University

Publications

Research Publications

F.M. Lastname, J. Doe, and R. Vasques, “Some Cool Title for a Paper," Journal Name, vol. 99, pp. 11-22, 2018.

Fields of Study

Major Field: Nuclear Engineering

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List of Symbols

ψ . . . . Angular Flux

ϕ . . . . Scalar Flux

Chapter 1: Introduction

The main idea behind this dissertation is to provide an alternative, improved solution for unfolding neutron spectra from given detector responses for the purpose of determining more accurate dose information. This chapter will outline the motivation for this problem.

1.1 Background and Motivation

Radiation is prevalent in our lives, whether it originates from background radiation, cosmic rays, medical processes, or nuclear reactors. Understanding the effects of radiation is crucial for the ability to utilize it as well as ensure the least harm comes from it. The study of health physics is concerned with, among other things, the physical measurements of radiation and the relationship that arises between radiation exposure and biological damage [**cember2017**]. Additionally, the effects of radiation on non-biological materials is another major area of study **(need citation)**. To determine the effects of any kind of radiation that has interacted with a material, the energy of that radiation must be known [**cember2017**].

The unit of radiation energy is the electron volt (eV) [**cember2017**]. This unit is derived from the energy required to move an electron through one volt of potential difference. The electron volt is equivalent to $1.6 \cdot 10^{-19}$ Joules. Typically, radiation can have a range of energy from meV ($10^{-3}eV$) to GeV ($10^{9}eV$). When quantifying the effects of radiation interacting with materials, the type of radiation must also be known [**knoll_2020**]. Due to their unique types of interactions, radiation is categorized into four categories: heavy charged particles, fast electrons, electromagnetic radiation, and neutrons [**knoll_2020**]. In the study of radiation, the energy range of $10eV$ to $20MeV$ is of most interest [**knoll_2020**] (p1). The lower limit of $10eV$ is chosen because that is the transition point above which radiation becomes ionizing [**knoll_2020**] (p1). Because of their importance in many nuclear reactions, thermal neutrons, which have energies as low as $40meV$, are an exception [**knoll_2020**] (p1).

Depending on the category and energy of the radiation, the types and effects of interaction vary widely [**evans**].

The ability to accurately measure and calculate radiation dose to within certain limits is a standard set my national and international government organizations [**doe-std-1098**]. On a regular basis, the capabilities of nuclear enterprises are tested against these standards through multi-organizational exercises **cite: either DOE O 420.1C, 10 CFR Part 830, or IER-538 CED4A Report**. The purpose of these exercises is to acquire detector responses through dosimeters that can be used to obtain dose information **10 CFR Part 830**. Acquiring dose information requires multiple steps from detector response to dose. First, the detector response needs to be unfolding to show the neutron spectrum. This process is not well defined and is currently under study to improve it. Second, that unfolded neutron spectrum must be converted to dose through reported energy-dependent conversion factors [**compendium_of_neutron_spectra**].

The study of neutron spectrum unfolding can be traced back to the 1950s [**poole1952**] with further work on developing specific neutron spectrum unfolding techniques in the 1960s [**habiger1964**]. The accurate unfolding and characterization of neutron spectra from detector responses in important in many fields of study and in practice. In the last 60-70 years, various methods have been developed to improve the accuracy and reliability of spectrum unfolding, including but not limited to: gathering information from proton recoil [**thomas1999**], using nuclear reaction products [**weyrauch1993**], time-of-flight methods [**tagliente1998**], threshold methods [**hecker1977**], and multiple sphere systems [**bonner1960**].

1.2 Dissertation outline

It goes like this.

Chapter 2: Neutron Spectrum Unfolding

This Chapter will contain all of the current neutron spectrum unfolding techniques, including the strengths and weaknesses of each.

2.1 Radiation Interaction with Matter

Before delving into the methods of neutron spectrum unfolding, a basis must be set for how neutrons interact with matter. Being uncharged particles, neutrons cannot be affected by electric fields and cannot be as easily manipulated into interactions as charged particles can. The likelihood of neutrons interacting with matter depends solely on the cross-section of interaction [**lamarsh_baratta_2018**]. The only options available are to use detection materials that have a high cross-section of interaction with neutrons or to use other materials with high cross-sections of interaction to cause the neutrons to slow down.

Neutrons can interact with matter in myriad ways. Because they are not charged particles, neutrons interact directly with the nucleus and see no effect due to the electron cloud around the nucleus [**lamarsh_baratta_2018**]. The types of interactions include: elastic scattering, inelastic scattering, radiative capture, charged-particle reactions, neutron-producing reactions, and fission. [**lamarsh_baratta_2018**]. Each type of interaction has a characteristic probability of occurring depending on the neutron energy. In other words, the cross-section depends on the type of interaction and energy of the incident neutron.

An example graph of interaction cross-section as a function of neutron energy is shown in **Figure below**.

get cross-section vs energy graph

Most radiation encountered by daily radiation workers has energies up to 20 MeV [**lamarsh_baratta_2018**].

2.2 Spectrum Unfolding

Spectrum unfolding requires math.

2.2.1 Detector Response Matrix

2.3 MAXED

An introduction about MAXED and the reasons it was developed will go here.

2.3.1 Description of the math of detector response unfolding

Talk about dual annealing, the maximum entropy method, χ^2 method.

2.3.2 Passive Neutron Spectrometer Response

The Passive Neutron Spectrometer provides similar capabilities to multisphere neutron spectrometers (like Bonner spheres), albeit in a single sphere of material. With the 55 TLDs arranged along the three Cartesian axes, each detector has a different thickness of material separating it from a potential neutron source. This arrangement effects a different response in each of the TLDs, which can be utilized in unfolding techniques.

A typical depth-averaged (I'll have described this in an earlier chapter/section) detector response from the PNS is shown in Figure 2.1.

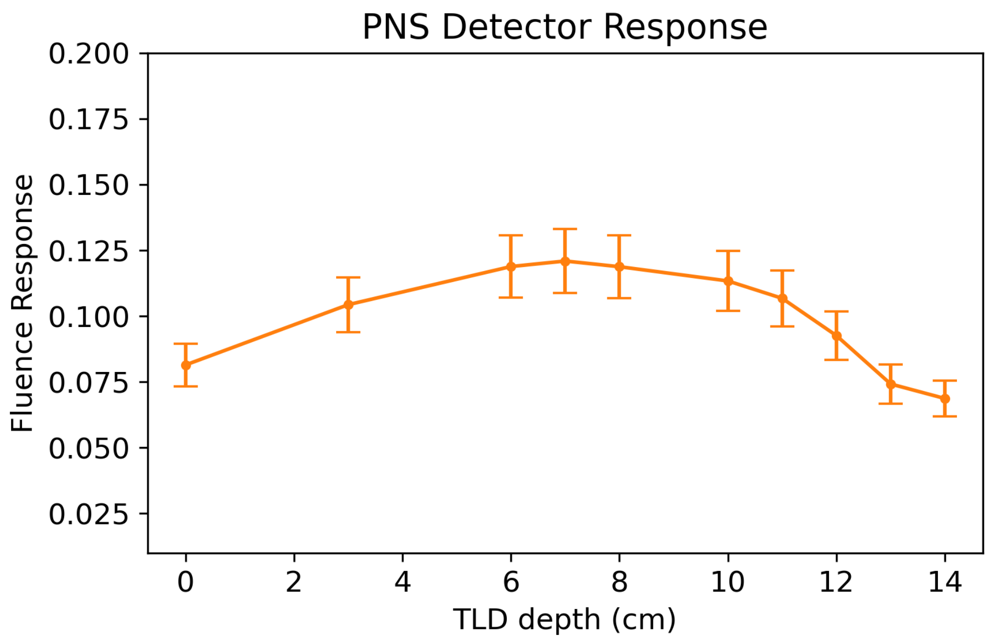

Figure 2.1: A depth-averaged detector response from the PNS in the presence of a Cf-252 neutron source.

2.3.3 Unfolding the Detector Response

(The math will be described in Section 2.3.1) The detector response from Figure 2.1 was used to unfold the neutron spectrum. As mentioned earlier, this detector response was achieved in the presence of a Cf-252 source. Knowing the correct spectrum allows for a good measurement of the accuracy of the algorithm. The inputs needed for MAXED to unfold the spectrum is a detector response, an initial guess at what the spectrum should be, and, as mentioned in Section 2.2.1, a detector response matrix. The following sections will show the accuracy of MAXED when the guess spectrum is varied and showcases the extreme sensitivity to the initial guess.

Because the true spectrum is known, the accuracy of the output of MAXED can be calculated and compared using the modal assurance criterion (MAC). (Put more information about it here) It gives a range (0 1], 1 being an exact match between two sets of data and anything lower is less similar.

$$MAC = \frac{|(Spectrum_{unfolded})^T(Spectrum_{true})|^2}{((Spectrum_{unfolded})^T(Spectrum_{unfolded}))((Spectrum_{true})^T(Spectrum_{true}))}. \tag{2.1}$$

Using the true spectrum

An initial point to check for the accuracy of MAXED is by using the true spectrum as the initial guess. The values for this spectrum were taken from the IAEA document Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes [**iaea_spec**]. Barring any other interactions, the MAXED code should get 100% accuracy on this example, but because the environment surrounding the PNS will reflect neutrons and affect the detector response, there will still be error. The results of this unfolding is shown in 2.2.

- DRM: Plane source DRM
- Guess Spectrum: Cf-252 spectrum

Using the true spectrum with a different DRM

Following the above example but with a DRM developing using a spherical source surrounding the PNS and directing neutrons inward. Both are very accurate, with MAC numbers very close to 1. Results are in Figure 2.3

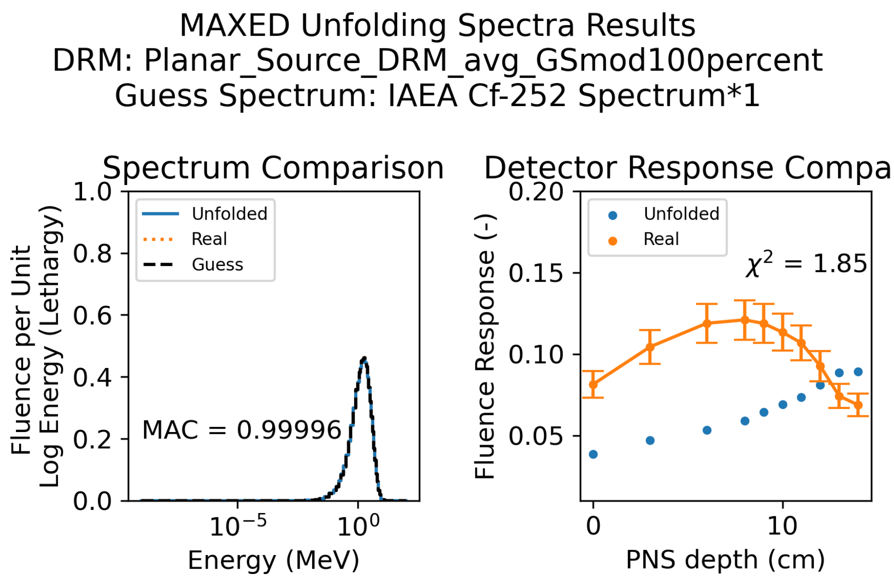

Figure 2.2: The results of the MAXED algorithm using a Cf-252 guess spectrum.

- DRM: Sphere source DRM
- Guess Spectrum: Cf-252 spectrum

Using the true spectrum multiplied by 0.9

Running MAXED with the plane-source DRM and using a modified Cf-252 spectrum as the input guess spectrum. The modification was performed by multiplying the spectrum by 0.9. Results are in Figure 2.4

- DRM: Plane source DRM
- Guess Spectrum: Cf-252 spectrum * 0.9

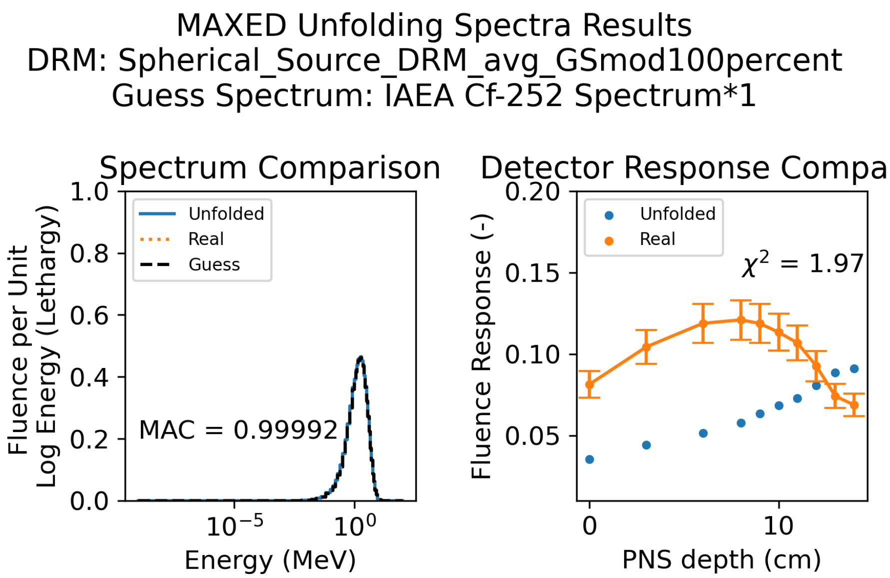

Figure 2.3: The results of the MAXED algorithm using a Cf-252 guess spectrum.

Using the true spectrum multiplied by 0.5

Running MAXED with the plane-source DRM and using a modified Cf-252 spectrum as the input guess spectrum. The modification was performed by multiplying the spectrum by 0.5. Results are in Figure 2.5

- DRM: Plane source DRM
- Guess Spectrum: Cf-252 spectrum * 0.5

Using a D2O moderated Cf-252 spectrum

Running MAXED with the plane-source DRM and using a D2O moderated Cf-252 spectrum. Notice that the MAC number is much smaller than 1. Results are in Figure 2.6

- DRM: Plane source DRM

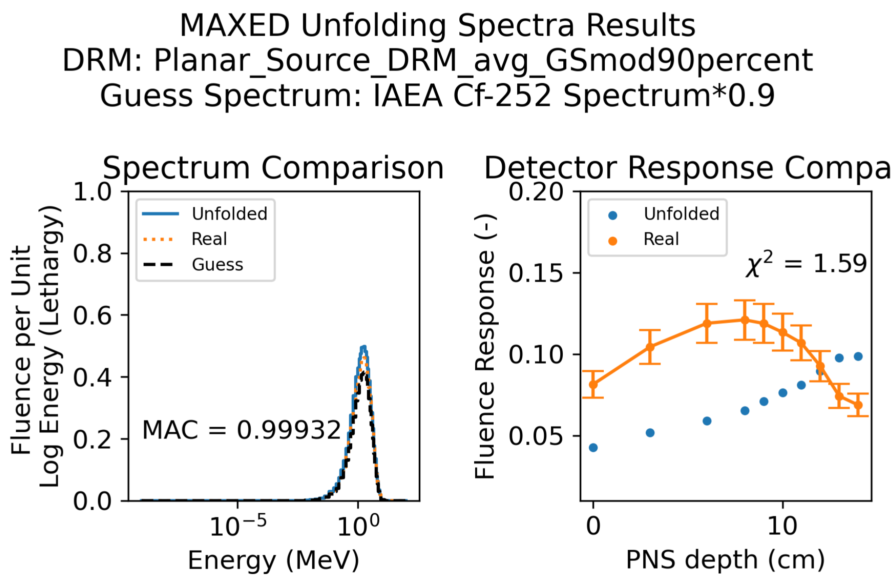

Figure 2.4: The results of the MAXED algorithm using a modified Cf-252 guess spectrum.

- Guess Spectrum: D20 moderated Cf-252 spectrum

Using a H2O moderated PuBe spectrum

Running MAXED with the plane-source DRM and using a H2O moderated PuBe spectrum. Notice that the MAC number is much smaller than 1. Results are in Figure 2.7

- DRM: Plane source DRM
- Guess Spectrum: H2O moderated PuBe spectrum

Using a randomly generated DRM

Once a different spectrum is used for input, the output of MAXED becomes highly inaccurate. Another test of the robustness is to try using a randomly generated DRM. The results are in Figure 2.8.

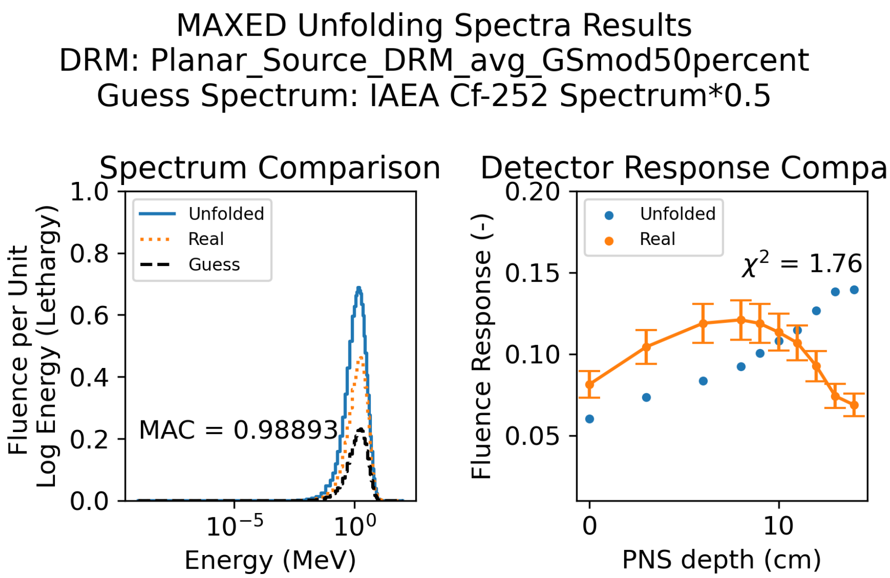

Figure 2.5: The results of the MAXED algorithm using a modified Cf-252 guess spectrum.

- DRM: Random DRM
- Guess Spectrum: Cf-252

Using a randomly generated DRM and modified guess spectrum

The effects of the random DRM are even more visible when the true spectrum is modified like above. In this case, the Cf-252 spectrum is multiplied by 0.5 and the results are in Figure 2.9.

- DRM: Random DRM
- Guess Spectrum: Cf-252 * 0.5

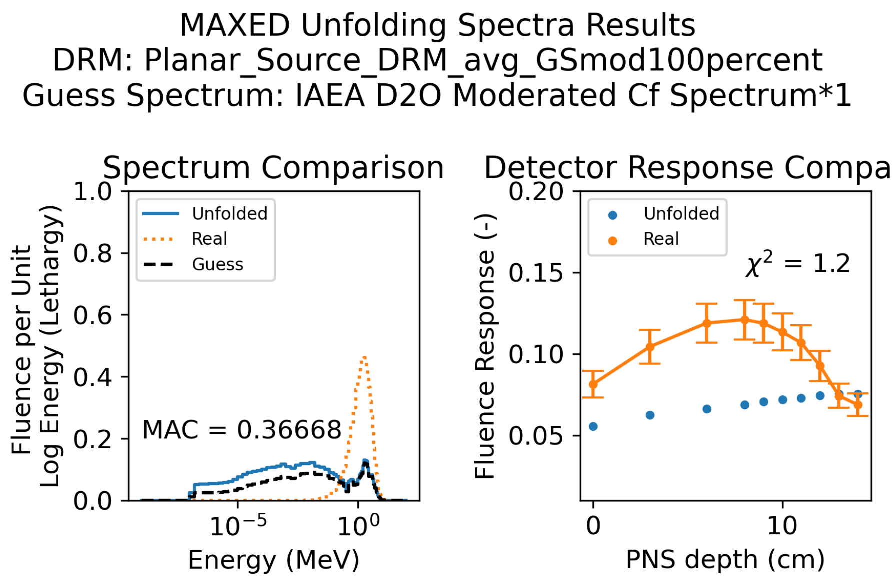

Figure 2.6: The results of the MAXED algorithm using a D20 moderated Cf-252 guess spectrum.

Thoughts on MAXED

When given very good information, the MAXED algorithm can perform neutron spectrum unfolding. This is highly dependent on the operator who provides the information to the algorithm. As shown in the examples above, the results of MAXED do not depart greatly from the initial guess spectrum.

At first, it appears that a randomly generated DRM performs well, but I think this is an artifact of the limitations of the MAXED algorithm. I believe that there are a great many local minima and the initial guess makes a very big impact. Additionally, when the guess spectrum is modified like in earlier examples, the effects of the randomness are more pronounced.

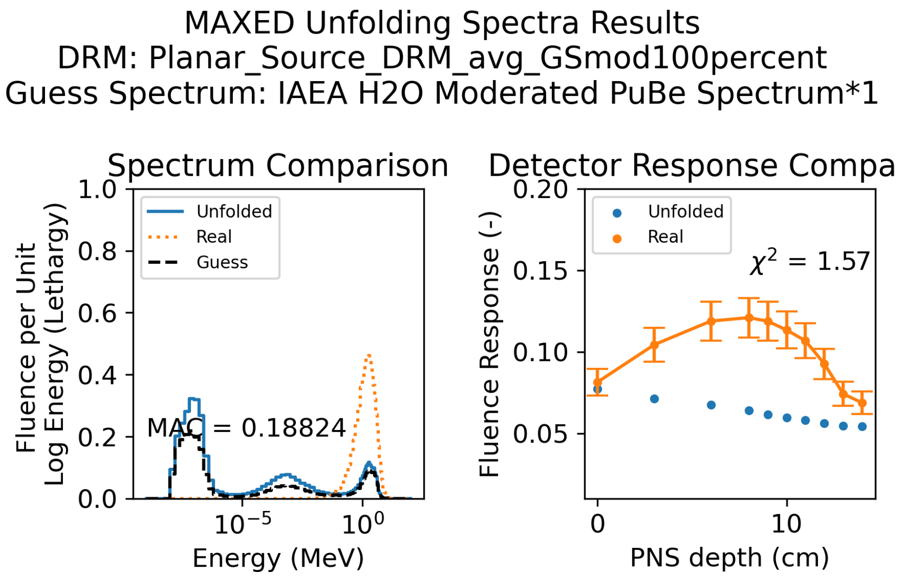

Figure 2.7: The results of the MAXED algorithm using a H2O moderated PuBe guess spectrum.

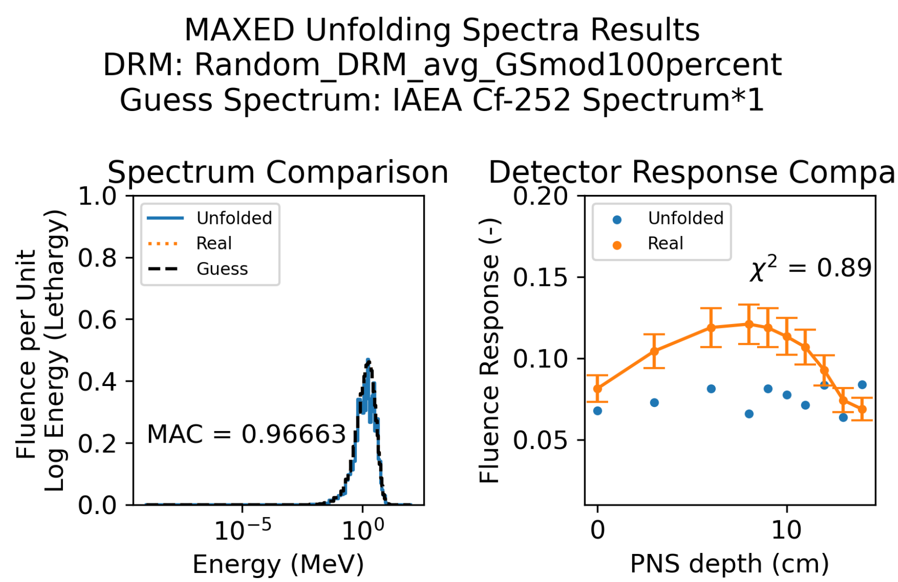

Figure 2.8: The results of the MAXED algorithm using a Cf-252 guess spectrum and a randomly generated DRM.

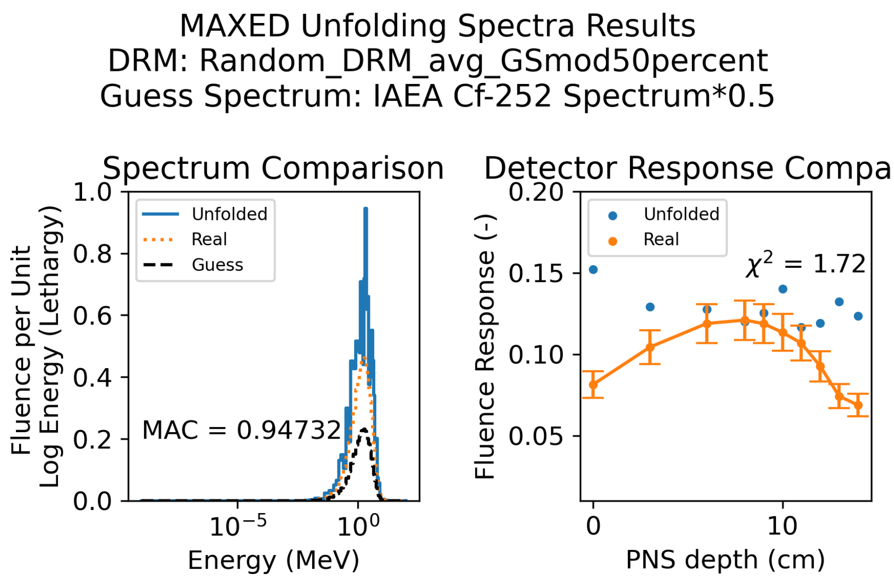

Figure 2.9: The results of the MAXED algorithm using a modified Cf-252 guess spectrum and a randomly generated DRM.

Chapter 3: Machine Learning/Neural Networks

This Chapter will contain all of the current machine learning and neural networks techniques.

3.1 Input Normalization

- The benefit of normalizing input data is that it will drastically reduce calculation time and it is very important to get good results. The data used in this paper has varying units and a vast range of values (ranging for multiple orders of magnitude). Large values used in neural networks use up much more storage space and significantly slow down computations. They used different normalization techniques (which were sometimes just a linear transformation rather than a normalization) to test the effects on the learning process. **??**

- Normalization is critical to getting the data in a readable and easily interpreted format. Without normalization, the network-based model may not be able to find a positive correlations between the variables. Almost all data in scientific studies will have been normalized before it is used. The normalization of the data scales it to the same range, which reduces analysis time and minimizes the bias in the ANN. This paper focuses on four normalization methods **??**

- Z-score Method (which is actually the same method that SciKit calls StandardScaler): $x = \frac{x-\mu}{\sigma}$
- Min-Max Method (SciKit_MinMaxScaler): $x = \frac{x_i - x_{min}}{x_{max} - x_{min}}$
- Median Method: $x = \frac{x_i}{Median}$
- Adjusted Min-Max Method $x = 0.8 * \frac{x_i - x_{min}}{x_{max} - x_{min}} + 0.1$

The concluded that the adjusted Min-Max Method was the best for their dataset, but they do not make any claims about it being better in general.

3.2 jude

Chapter 4: Unfolding Neutron Spectra with Neural Networks

This Chapter will contain all of the process of developing a neural network to unfold neutron spectra.

Chapter 5: Validation of Unfolding Neutron Spectrum Using a Neural Network

This Chapter will contain all of the work done validating the neural network for unfolding spectra.

Chapter 6: Comparing Neutron Spectrum Unfolding Techniques

This Chapter will compare the neural network unfolding method with other unfolding techniques.

Chapter 7: Unfolding the Spectrum with New Data

This Chapter will showcase the results of using the neural network to unfold data from a new real world detection using the PNS.

Chapter 8: Conclusions

This is your final chapter. It does not have to be titled “Conclusions"; it could be “Discussion", or whatever else you prefer.

I am going to use this chapter to talk about references. All your references should be in the references.bib file, in the same folder as this source file. Only entries that are actually referenced in the text will show up, so you do not have to delete entries from the references.bib file. References will appear in the order they are cited in the text. You can look at the references.bib file to see how to enter each of the references in the following examples.

For papers in proceedings you need: authors' names, title of paper, title of proceedings, location [city, state (if in the US), or city, country (if abroad)], dates (month, days, year). See examples in [**proc1**, **proc2**, **proc3**].

For papers in journals you need: authors' names, title of paper, full name of journal, volume, number (if exists), pages, year. See examples in [**artic1**, **artic2**, **artic3**].

For book chapters or papers in books you need: authors' names, title of chapter or paper, title of book, name of editors, name of publisher, pages, year. See examples in [**chapter1**, **chapter2**, **chapter3**].

For books you need: authors' names, title of book, name of publisher, year. See examples in [**book1**, **book2**, **book3**].

Appendix A: This is an Appendix

You can have as many appendices as needed.