Neutron Spectrum Characterization

Nicholas Quartemont

***Abstract*—This paper outlines a foil activation experiment in the Air Force Institute of Technology neutron pile with the purpose of unfolding the neutron flux in stringer 2. Due to facility limitations, the unfolding analysis was conducted on an experiment with a test snout performed at the National Ignition Facility (NIF). Foil activation experiments are an indirect method of measuring an incident neutron flux and are preferred in high flux environments that will damage electronics or for size constraints. Foil activities produced from threshold and non-threshold reactions were analyzed using a high purity germanium detector that resulted in time-corrected activities post-irradiaiton of in the range of 100 Bq to 10 kBq. The NIF experiment utilized aluminum, gold, indium, and zirconium foils varying mass at the pinhole, basket, and kinematic base locations of the snout. The irradiation planned for the neutron pile also included tungsten and manganese. The incident neutron fluence was unfolded from the activities and nuclear data with a selected NIF initial spectrum and a flat spectrum. The results for the pinhole and basket show varying physical results, while both have p-values under 0.01. The results for the basket do not match intuition and likey requires a better starting spectrum. The result for the kinematic base shows a similar result to the pinhole. However, the p-value is near 0.9, which indicates the result is not representative of the activities produced. The kinematic base is the largest change from the initial spectrum and requires a better starting spectrum.**

***Index Terms*—neutron flux unfolding, foil activation, high purity germanium, STAYSL**

I. Introduction

CHARACTERIZING the energy dependent neutron environment from neutron sources has many application to the nuclear sciences community. Determining a neutron flux is important for experiments where the neutron flux requires validation or is not well modeled. Neutrons can be detected using a variety of methods, such as Bonner spheres, Long counters, He-3 based detectors, or proton recoil scintillators [1]. Foil activation experiments can also be performed to acquire an indirect measurement of the incident neutron fluence on a set of activation foils. Activation experiments are essential for testing that requires small geometry to fit in the apparatus or in situations where electronics equipment for higher fidelity measuring techniques will be damaged.

This work aims to characterize the neutron spectrum in the Air Force Institute of Technology (AFIT) Building 470 neutron pile constructed in the 1960s, which contains a plutonium-beryllium (PuBe) neutron source [2]. Previous studies have accomplished results indicating changes to the neutron source term and modeled levels of fluxes [3], [4]. However, the source characterization is still not entirely known.

The neutron source characterization is acquired with a foil activation experiment. The foils are analyzed using a calibrated high purity germanium (HPGe) detector to determine time corrected activities post-irradiation. The HPGe requires calibration for energy and efficiency to back out the foil activities. The incident neutron flux is determined using Pacific Northwest National Laboratory (PNNL) STAYSL, which uses generalized least-square minimization to determine the flux for given foil activities and nuclear data.

The pile activation results are not used in the final neutron flux analysis due to issues with the HPGe at AFIT. Instead, this work analyzes an experimental setup at the National Ignition Facility (NIF). The NIF foil activation experiment was performed on a snout for a shot performed in March 2018 [5]. The goal of the NIF experiment is to characterize the NIF source in the aluminum snout which has applications for exploring cross-section uncertainties if there are unexpected results.

II. Problem Description

The neutron spectrum characterization requires information from the foil activities. The theory and problem statement contributing the foil activation involves the neutron flux environment, foil activation, HPGe spectroscopy, and neutron flux unfolding. Supporting documentation and work performed is available on Github [13].

A. Building 470 Pile Neutron Environment

The neutron pile was modeled in MCNP version 6.1 based on previous work to gauge expected activation rates and to determine saturation activities [3]. The setup of foil placement and PuBe source is shown in Figure 1. The pile has stringers which can be pulled out to place experiments. The stringers have fabricated placements for the source and foils.

The neutron environment from the PuBe source transported to the stringer 2 location determines the activation rates for the foils. The starting spectrum ends at 11 MeV and peaks near 3.5 MeV. The PuBe source spectrum is shown in Figure 2. The transported spectrum to stringer 2 is shown in Figure 3.

The neutron flux is heavily thermalized compared to the starting spectrum. The selection of activation foils was determined by the modeled foil activation rates, which will be discussed later.

B. NIF Snout Experiment

A passive foil activation experiment was performed in 2018 at the NIF. A snout composed of aluminum is mounted to the Target and Diagnostic Manipulator (TANDM) 90-348. Three foil activation diagnostic packs of aluminum, zirconium, indium, and gold were placed in the nose cap pinhole (7 cm from source), filter basket (41 cm), and kinematic base (110 cm). The aluminum foil was not used in the pinhole. Figure 4 displays the snout with the activation foil sites [5].

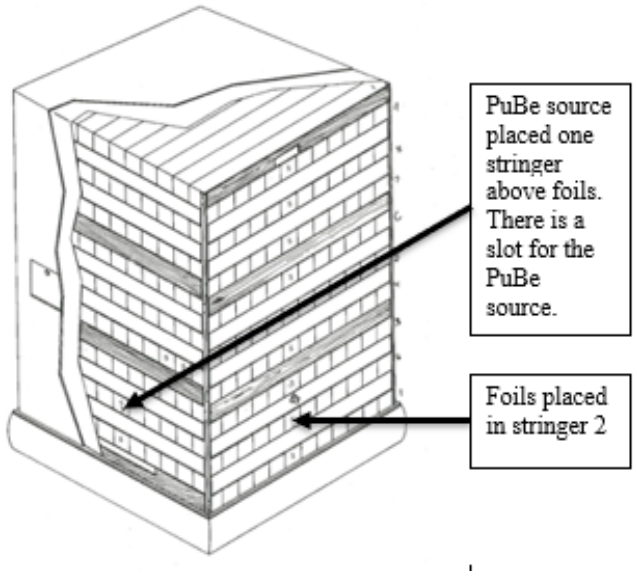

Fig. 1. Activation foil setup for Building 470 irradiation.

The NIF source is a deuterium-tritium (DT) capsule which have neutrons at a nominal energy of 14 MeV. The spectrum of neutrons used as a source term is shown in Figure 5.

C. Foil Activaiton

The foils intended for activation produces radioactive isotopes during the course of irradiation. Foil activation can be used with published nuclear data to provide an estimate of the incident flux on the foils by unfolding techniques. The production rate of radioactive isotopes is negated by radioactive decay processes, which place an upper limit on the radioactivity of a foil [1]. The saturated activity (A_∞) is equivalent to the reaction rate (R), which is a function of the energy dependent flux (ϕ), the macroscopic reaction cross-section (Σ), and the volume of the foil (V_{foil}). The energy term (E1) is zero in many cases; however, threshold reactions require the incident neutron to be of higher energy to enable the reaction channel. The saturated activity for a given reaction is given by:

$$A_\infty = R = \int_{E1}^{E2} \phi(E)\Sigma(E)_{Activation} V_{foil}\, dE \qquad (1)$$

A correction needs to be made in cases where the activation is not sufficient to fully saturate the foil. At six half-lives a foil will have reached approximately 98% of its saturation activity, neglecting spatial and energy self-shielding effects [1]. The activation of the foil for a given irradiation time ($t_{irradiation}$) is given as a function of the decay constant:

$$A_0 = A_\infty(1 - e^{-\lambda t_{irradiation}}) \qquad (2)$$

Experimental measurements also can be corrected to deduce the original activity of the foil, immediately after irradiation. The measured counts (C) is reduced by the background counts (B). A factor for the decay time between the end of irradiaiton and the start of counting (t_{decay}) corrects for the radioactive decay during that timeframe. A similar correction factor based on the count time (t_{count}) provides a correction for decay during counting. Additionally, the detector efficiency for the given gamma-ray energy (ϵ) and relative gamma intensity (I_γ) must be taken into account. The gamma intensity may

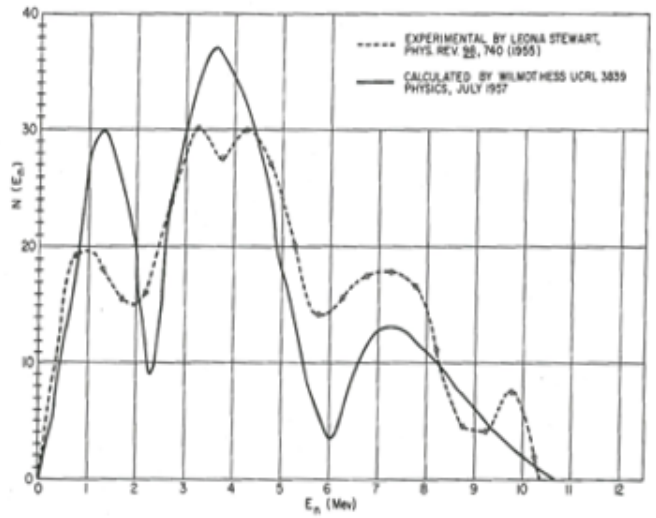

Fig. 2. PuBe neutron emission source spectrum.

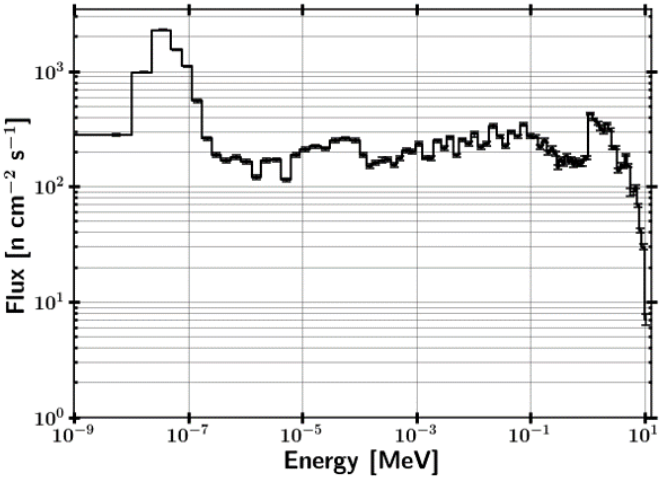

Fig. 3. Foil activation neutron flux environment (all statistical errors are under 1.5 percent).

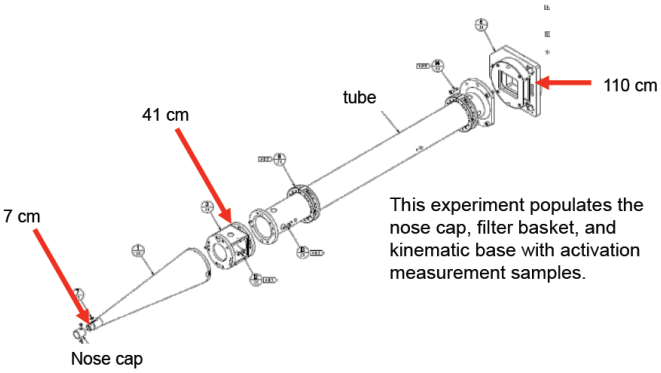

Fig. 4. Passive NIF snout foil activation locations.

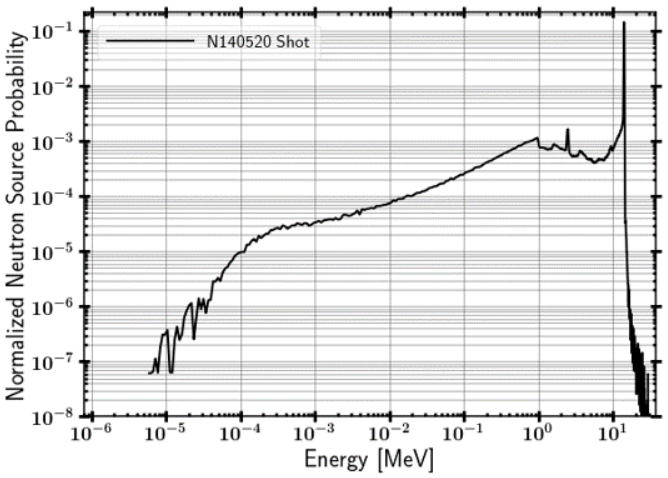

Fig. 5. NIF DT neutron source spectrum.

also include a branching ratio if applicable to the decay mechanism. All corrections included, less shielding effects, provide a formulation for converting counts to post-irradiation activity as:

$$A_0 = \frac{\lambda(C-B)e^{\lambda t_{decay}}}{\epsilon(1-e^{-\lambda t_{count}})I_\gamma} \tag{3}$$

The formula can be simplified in the limit of irradiation times much less that the half-life of the activation products. In this case, the reaction rate is much larger than the decay from radiation, so the rate of production of the radioisotope is driven only by the reaction rate. The time integrated flux, or neutron fluence (Φ), can be used to determine the total reactions (R_{total}) over an irradiation period, given by:

$$R_{total} = \int_{E1}^{E2} \Phi(E)\Sigma(E)_{Activation} V_{foil}\, dE \tag{4}$$

The foils selected must meet several requirements for this experiment. The method of foil activation has been studied in-depth in the nuclear sciences and engineering community. A list of the various requirements that are of importance for a neutron activation foil experiment with energies in the range of thermal to approximately 11 MeV is summarized below [1], [6], [7].

The reaction neutron cross-section is extremely important for foil activation, and there are a few key parameters that should be considered. First, the magnitude of the cross-section determines the reaction rate of the product nuclides. A large cross-section allows for more activation, and therefore better results when analyzing the activation foils. Second, the uniqueness of the cross-section shape is used to unfold the incident neutron energy spectrum. An (n,γ) cross-section may peak in a particular region, which is essential to providing information of the neutron flux in that energy region. Alternatively, a threshold reaction, such as an (n,2n), is important for providing information of the flux at higher energies. Third, the selected foils for an experiment should cover the entire energy range of the incident neutron flux.

The nuclear data must be well characterized over the neutron energies. Additionally, the uncertainty in the reaction cross-section and decay mechanisms must be low to not provide misleading results.

The decay constant of the product nuclides is important. The half-lives applicable for a particular experiment depend on the time post-irradiation that the foils can be counted. A long lived radioisotope will be available for counting for longer times, but the activity will be lowered from the lower decay constant. The opposite being true for short half-lives. A half-life on the order of an hour to a few years is in the right direction; however, the half-life must also be balanced with the production of the radioisotope to understand the entire picture.

The elemental and chemical purity of the activation foil should be well known. An unknown composition foil will likely cause erroneous results.

Interfering reaction channels and decay emissions should be avoided. An example of this is natural copper, which has multiple 511 keV emissions from different reaction channels. It is not feasible to distinguish these gamma-rays to determine activation in counting. Similar problems arise in multi-isotope materials that have multiple reactions producing the same nuclide. For example, a Cadmium-106 (n,γ) reaction produces the same isotope as a Cadmium-108 (n,2n) reaction.

The activation foil should be optically this so as to not cause perturbations of the neutron flux. An additional benefit of relatively thin foils is that the gamma-ray emissions are not significantly attenuated through self-shielding. The neutron flux should ideally also not be changing substantially over the foil region. In general adding additional foils helps to improve the unfolding results, as long as the entire foil set remains optically thin to the , [8].

The decay nature of the product nuclide should be a gamma-ray emitter. Gamma-ray detection can provide fine energy resolution to determine activation. The discrete gamma-ray emissions provide a means of determining the source and magnitude of the the foil activation. The energy of the gamma is also of importance. Semiconductor detection methods have a peak intrinsic efficiency near 100 keV with some variance depending on if it p-type or n-type.

D. HPGe Calibration

HPGe detectors produce an information carrier as an electron-hole pair for every 3 eV of energy deposited in the detector [9]. Gamma radiation spectroscopy can be used to identify radioactive sources based on the pulse height amplitude produced in the detector for a proportional detector. Gamma radiation interacts with matter though the photoelectric effect, Compton effect, and pair production. Scattered photons have a continuum of energies under the full energy peak (FEP) [1].

An energy calibration curve can be constructed to map channel to incident energy using a least square fitting technique. A linear distribution is appropriate for an HPGe. Non-linearities will may introduce errors up to five percent at lower energies near 100 keV [1]. The FEP centroid can be used to determine the radioactive source by the emission energy.

The HPGe efficiency as a function of energy can be calibrated with a known multi-nuclide source and measurements of the experimental setup. The absolute efficiency can be calibrated at a source distance to obtain unknown source activity [1]. The absolute efficiency (ϵ_{abs}) can be obtained by:

$$\epsilon_{abs} = \frac{\text{\# Events Recorded}}{\text{\# Radiation Quanta Emitted}} \tag{5}$$

A calibrated efficiency curve can be used to find the source strength of samples, scaled by the distance to the detector. There are a few types of fits that are appropriate for efficiency curves. Piecewise curves can work in certain applications. A common efficiency curve is given as a function of N fitting parameters and a reference enrgy (E_0):

$$ln(\epsilon_{abs}) = \sum_{i=1}^{N} a_i (ln(\frac{E_\gamma}{E_0}))^{i-1} \tag{6}$$

E. Neutron Flux Unfolding

Foil activation experiments are a well established method for determining an in- cident neutron energy spectrum. The foil are activated under a nearly equivalent neutron ux, which serves to activate the foil samples through various nuclear reaction channels. Each of the reactions has a unique response function with respect to the neutron ux. The nuclear data and activities of the foils can be used to unfold the incident neutron energy spectrum.

A few examples of studied methods of unfolding matrix inversion, least-square spectral adjustment, and stochastic algorithms [10]. Matrix inversion can lead to non-physical results, such as negative fluxes [10]. Stochastic methods rely on random sampling to derive a best-fit or average over a group of reasonably well-fitting spectra [10].

The least-squares method minimizes the chi-square based on a guess spectrum, activation information, and nuclear data [11]. The least-squares method is also known as spectral adjustment and can incorperate more information, most notably the underlying nuclear data, into the determination of the resultant spectrum [11]. The optimization is performed to minimize varying versions of the chi-square statistic among an energy group structure for the flux and nuclear data.

The general formulation of the least-squares method is derived from minimizing the activation results to the nuclear data and input spectrum [11]. The chi-square (χ^2) is given as per degrees of freedom (n) as a function of of the uncertainty, activation rates, nuclear data, and measured results. The chi-square formulation of the least-squares approach can be reduced if there is no time dependency of the nutron flux as:

$$\frac{\chi^2}{n} = \frac{1}{n} \sum_{i=1}^{m} \frac{(\sum_{j=1}^{N} \Sigma_i(E_j)\ \Phi(E_j) - \frac{A_i}{V_{Foil}})^2}{\sigma_i^2} \tag{7}$$

Providing an initial spectrum is often required for the unfolding methods. The activities produced for the foils is more often highly degenerate, where an infinite amount of spectra could provide the same end-point. The initial spectrum allows for the insertion of more physics based results to have an impact on the overall result. For neutron spectra, an initial guess spectrum is often created with a particle transport code or a deterministic solution.

The foil activities are used with the underlying nuclear data to unfold the neutron spectrum using Pacific Northwest National Laboratory (PNNL) STAYSL. STAYSL relies on least-squares spectral adjustment based on the chi-square of the measured activities to determine the incident neutron flux [12].

III. Description of Work

A. Foil Selection / Irradiation Parameters

The selected foils for the experiment are summarized in Table I. The foils were selected based on availability and usability in the nuclear data libraries used by STAYSL.

The irradiation time in the neutron pile was planned on ten days. This time was chosen to build up the enough activity to measure the activities. Specifically, Au-197 (n,2n) has a very long half-life, so approximately four half-lives of Au-196 were used. The expected activities post irradiation is summarized in Table II.

The simulated environment in MCNP resulted in no feasible reactions in the high energy region, such as the (n,2n) threshold reactions. The lack of pinning at high energy has a potential issue for the neutron flux unfolding, where there is no reaction pinning the high end of the neutron energy spectrum.

B. HPGe Characterization

The HPGe detection system can be streamlined compared to a traditional nuclear counting experiment. An ORTEC HPGe was connected to a DSA1000 which functions to replace many components necessary for a nuclear detection system. The DSA1000 was connected to a computer, which has a multi-channel analyzer (MCA) data acquisition software (Genie 2000 was used for this experiment). The bias voltage is set to 4,000 V. The gain was set so that the dynamic range of gamma ray energies of interest is measurable on the MCA. The course gain was set to 20 and the fine gain to 1.5.

The HPGe was characterized using a multi-nuclide source. The isotopes gamma decay energies in the source range from 60 keV from Am-241 to 1836 keV from Y-88, which covers the energy range of interest for the foil analysis.

The HPGe energy calibration utilized a linear relationship to map channel to energy. The channel to energy calibration is shown in Figure 6. The slope of the line is linear, which was expected.

The efficiency calibration was conducted at 10 cm and 5 cm from the base of the HPGe. The solid angle for a quarter inch radius foil at the 10 cm range is 0.66 radians, which is notably less than the idealized point source simplification of 0.79 radians.

An malfunction in the HPGe occurred prior to the completion of collecting data for the 5 cm case. The error prevented additional data acquisition for the building 470 pile portion of this experiment.

TABLE I
ACTIVATION FOILS SELECTED FOR IRRADIATION IN NEUTRON PILE.

Foil (thickness)	Reaction	Half-life	Threshold [MeV]	Decay Radiation [keV] (Intensity)	Purity [%]	Mass [g]
In (0.005" x2)	In-115 (n,g) In-115m	54.29 min	Thermal	1293.56 (0.848)	99.99	0.221(7)
	In-115 (n,n') In-116m	4.49 hrs	0.336	336.24 (0.459)	99.99	0.221(7)
Al (~2mm x4)	Al-27 (n,a) Na-24	15.00 hrs	3.25	1368.63 (0.9999)	99	3.395(3)
Au (0.005" x2)	Au-197 (n,2n) Au-196	6.17 days	8.11	355.7 (0.87)	99	0.577(2)
	Au-197 (n,g) Au-196	2.69 days	Thermal	411.8 (0.9562)	99	0.577(2)
W (0.005" x2)	W-186 (n,g) W-187	24.00 hrs	Thermal	685.51 (0.332)	99.98	0.627(2)
Mn (0.068 mm to 0.077 mm) x4	Mn-55 (n,g) Mn-56	2.58 hrs	Thermal	846.8 (0.9885)	99	0.266(0)
Zr (Not used in Pile Experiment)	Zr-90 (n,2n) Zr-89	78.41 hrs	12.1	909.2 (0.9904)	N/A	N/A

TABLE II
ACTIVATION INFORMATION FOR SELECTED PILE FOILS.

Reaction	A_{inf} [Bq]	A_{0} [Bq]	Count Time to 10,000 Counts (at 1% efficienty) [hrs]
W-186 (n,g) W-187	176.90	175.52	9
In-115 (n,g) In-115m	1394.07	1394.07	1
Au-197 (n,g) Au-196	820.33	684.87	7
Mn-55 (n,g) Mn-56	256.32	256.32	3
All others	<1.0	<1.0	N/A

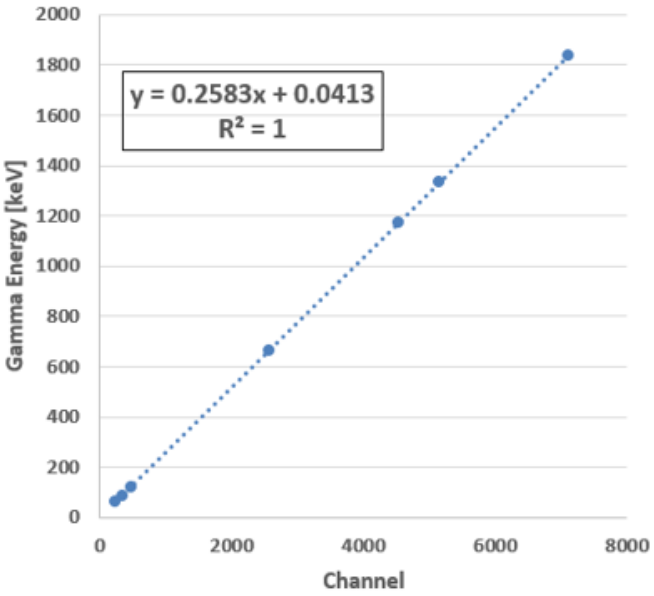

Fig. 6. HPGE energy calibration curve using a multinuclide source.

C. NIF Snout Experiment Activities

The HPGe analyzed dataset used for the NIF experiment was provided from Lawrence Livermore National Lab (LLNL). The counts per channel files were also provided. A validation test was performed with Los Alamos National Laboratory's Peak Easy on the pinhole results for the indium foil. The main In-115m peak at 336 keV is shown in Figure 7. The foils were 1 mm thick with the exception of the gold foils, which were 0.1 mm thick. The activities presented are large enough for accurate counting in an HPGe.

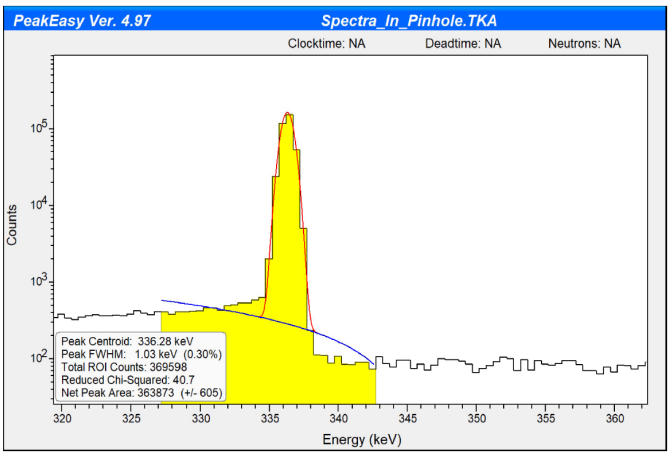

Fig. 7. 336 keV In-115m peak identification

There was general agreement between the counts for In-115m and In-116m. The counts identified by LLNL resulted in 361,000 $+/-$ 0.23% for In-115m and 1,383 $+/-$ 2.89% for In-116m. The calculated results from Peak Easy determined 364,000 $+/-$ 0.38% for In-115m and 1,402 $+/-$ 3.8% for In-116m. There is slight disagreement in the uncertainties. It is expected that multiple peaks are used to determine the overall uncertainty. A summary of the foils and activations used for the snout experiment is given in Table III. The value of "sig-phi" was used in STAYSL.

D. Unfolding NIF Experiment with STAYSL

STAYSL has several modules that are used to unfold the neutron spectrum from the calculated activities. The main components used in this analysis are SHIELD, SIG PHI Calculator, and PNNL STAYSL. The Beam Correction factor was not used because the NIF irradiation time is much less than the half-lives of the reaction products.

A complete walkthrough of the analysis is available on Github [13]. SHIELD was used to generate energy dependent neutron self-shielding factors for non-threshold reactions, which feeds into STAYSL. SHIELD is not used on high energy threshold reactions because there is negligible shielding.

The SIG PHI Calculator was used to consolidate all of the reaction information. Additionally, this module generates

TABLE III
ACTIVATION INFORMATION FOR THE NIF EXPERIMENT FOILS.

Kinematic Base						
isotope	mass (g)	A0 (Bq)	N0 (nuclei)	Percent Error	Gamma Self Shielding	"sig-phi" (at/at-s)
Au196g	3.733	5.74E+02	4.42E+08	1.60	0.974	3.98E-14
Au198	3.733	6.63E+02	2.23E+08	1.20	0.980	1.99E-14
In115m	14.35	5.57E+03	1.30E+08	1.20	0.950	1.82E-15
In116m	14.35	2.12E+05	9.97E+08	1.60	0.998	1.33E-14
Zr89	12.555	1.13E+03	4.61E+08	1.50	0.980	5.59E-15
Na-24	12.56	3.63E+03	2.83E+08	7.90	0.993	1.02E-15
Basket						
Au196g	0.9393	9.47E+02	7.29E+08	1.20	0.974	2.61E-13
Au198	0.9393	2.00E+02	6.72E+07	1.20	0.980	2.39E-14
In115m	0.4189	9.30E+02	2.17E+07	1.20	0.950	1.04E-14
In116m	0.4189	1.69E+04	7.91E+07	2.80	0.998	3.61E-14
Zr89	0.2626	1.76E+02	7.15E+07	1.10	0.980	4.15E-14
Na-24	0.0962	4.11E+02	3.20E+07	1.20	0.993	1.50E-14
Pinhole						
Au196g	0.148	6.97E+03	5.37E+09	1.30	0.974	1.22E-11
Au198	0.148	1.07E+02	3.58E+07	5.30	0.980	8.08E-14
In115m	1.182	1.23E+05	2.87E+09	0.70	0.950	4.88E-13
In116m	1.182	1.53E+05	7.18E+08	2.00	0.998	1.16E-13
Zr89	1.008	2.77E+04	1.13E+10	1.00	0.980	1.71E-12

gamma-ray shielding factors. The input was generated from this information and the nuclei production information.

STAYSL requires a starting guess spectrum. For this work, the NIF source was binned into the 140 group STAYSL structure. The flux was scaled by the spherical divergence to the foil locations.

STAYSL was completed for the pinhole, basket, and kinematic base for two cases. First, a guess spectrum of the NIF source was used with 100 percent flux uncertainty up to 13 MeV. The flux uncertainty from 13-15 MeV was set to five percent for the pinhole based on the reaction cross-section and threshold reactions expected results. Less was known about the resultant spectra for the kinematic base and basket, so the 13-15 MeV flux uncertainty was set to 100 percent. STAYSL was ran iteratively using STAYSL.py until the χ^2 changed by less than 0.1. The product spectrum is used as the guess spectrum for subsequent iterations. The goal to generate a resultant spectrum that matched the nuclear data and activity. The flux uncertainty was not updated until the solution converged based on the χ^2. The degrees of freedom (ν) for the pinhole is 4, because there are 5 foils. The other sets have 5 degrees of freedom.

The second method of iteratively solving started with a flat guess spectrum. A flat guess spectrum utilizes no a priori information about the flux, so it is a good indicator if the result matches up with the NIF guess spectrum iterations. The flat guess spectrum started with 100 percent uncertainty in all energy groups. For the NIF experiment, the temporal aspect of the flux is averaged out, so the values presented by STAYSL are really the neutron fluence.

IV. RESULTS

The unfolded results from STAYSL for the pinhole, basket, and kinematic base are shown in Figures 8 - 10. A summary of the χ^2 values and associated p-values are provided in Table IV. The basket results are truncated to a minimum fluence of $1\ n-cm^{-2}$.

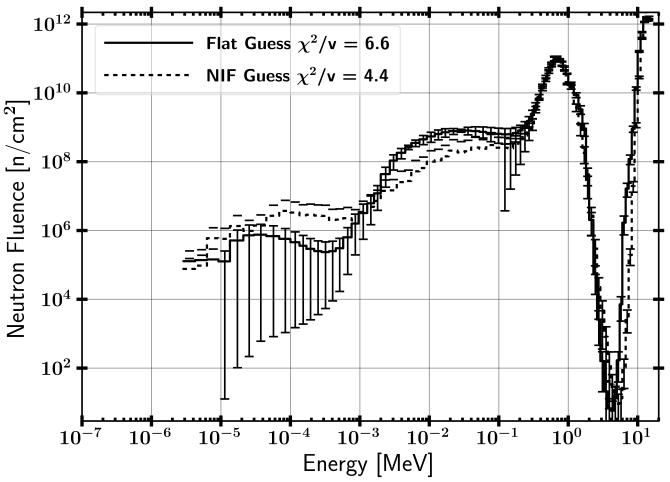

Fig. 8. Unfolded Spectrum for pinhole starting with NIF and flat guess.

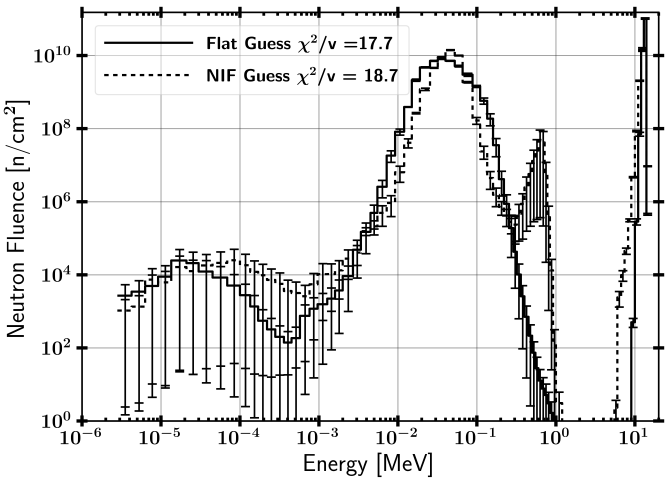

Fig. 9. Unfolded Spectrum for the basket starting with NIF and flat guess (Truncated at $1\ n-cm^{-2}$).

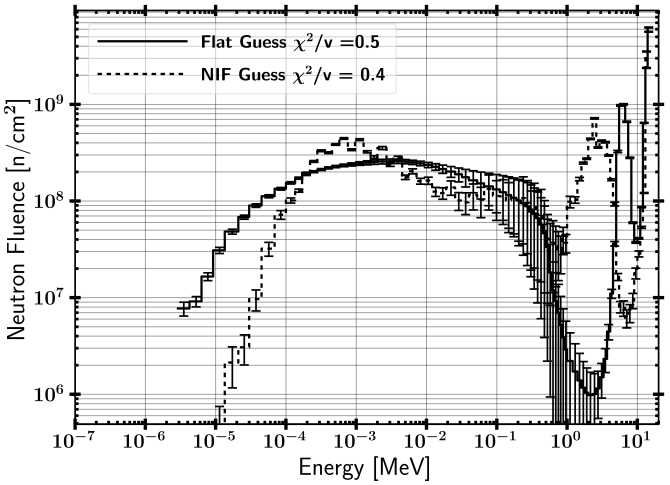

Fig. 10. Unfolded Spectrum for the kinematic base starting with NIF and flat guess.

TABLE IV
SUMMARY OF UNFOLDED RESULTS FOR PINHOLE, BASKET, AND KINEMATIC BASE.

Location	χ^2 / ν	ν	p-value
Pin NIF Guess	4.4	4	0.0015
Pin Flat Guess	6.6	4	3e-5
Basket NIF Guess	18.7	5	1e-18
Basket Flat Guess	17.7	5	1e-17
Kinematic Base NIF Guess	0.35	5	0.88
Kinematic Base Flat Guess	0.53	5	0.78

The results show good generally good agreement between the NIF guess and flat spectrum. No modeling information was available to use as a guess spectrum. The χ^2 values can be iterated to shrink the value; however, there is not a reason to do so past when the iterator stops. Non-physical results might be created.

The pinhole results in Figure 8 show that there is a steep dropoff in flux as energy decreases, which was not expected. The high energy bins at 13-15 MeV have very good agreement with expected values; however, the rest of the spectra was unexpected to some extent. The large epithermal peak energy is approximately 800 keV; which is approximately the first excited state in Al-27 (843 keV). There is no physical basis for the near complete removal of neutrons between 1 and 10 MeV, while the source distribution indicates there should be a large portion present. The peak is shaped like an neutron evaporation spectrum. Past the epithermal peak, there is a decaying thermal tail. Starting from a flat spectrum produced nearly identical results, so it would have been ideal to have a threshold reaction near 1 MeV. The p-values for the pinhole indicate the result is very likely in both cases. Again, there is some degeneracy in the solution.

The basket results are similar to the pinhole with some key differences. First, the main 13-15 MeV peak has dropped by approximately six orders of magnitude, which is not representative of the linear attenuation of 34 cm of aluminum ($\Sigma \approx 0.1$ cm^{-1}). There is good agreement between the flat and NIF guess spectrum, so the threshold reactions are indicating the dropoff. Second, the neutron flux between approximately one to ten MeV is nearly removed. There is not a process that would remove all of the source neutrons in this region, but the result appears for the flat starting spectrum as well. The last difference is that the 800 keV peak only is present in the flat spectrum, and both guess spectra result in a peak at approximately 40 keV. The p-values for both spectra indicate that the result matches the activation. The result may have been improved with a better initial guess.

The kinematic base has the largest variance in results. At 13-15 MeV, the neutron flux is at approximatley 10^9, which is more in line with expectations. The NIF guess and flat guess both have an epithermal energy peak; however, the location is different. In both spectra there is a large thermal tail from scattering. The results for the kinematic base are likely the farthest from the true distribution as the initial guess spectrum was farthest from reality. The p-values for the kinematic base indicate that the resultant spectra are not indicative of the neutron environment.

V. CONCLUSIONS

Characterizing the neutron energy spectrum in the snout experiment at the NIF provided mixed results. The foil activities and underlying nuclear data were applied in STAYSL to unfold the spectrum with STAYSL for the pinhole, basket, and kinematic base locations in the snout. The results in each case were not expected. An epithermal peak was produced and higher energy neutrons were removed, which does not align with anticipated results. The reduced χ^2 result indicated that the pinhole and basket unfolds matched the activation results.

The unfolded neutron spectrum results highlight and reinforce necessity of having an initial guess spectrum for the generalized least-squares minimization. Each unfold, completed with the NIF starting spectrum and a flat spectrum, produced similar results; however, there are some differences that require attention. The kinematic base in particular did not converge to a similar solution over a large energy range. The results presented would be improved with a better starting guess for the initial spectrum.

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