

# MODERATION OF THE AmBe SOURCE APPLIED ON FAST NEUTRONS STIMULATED EMISSION COMPUTED TOMOGRAPHY

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## ABSTRACT

Nowadays, new proposals for diagnosis are being created, which always aim to decrease the dose to the patient and improve image quality, among them there is the Neutron Stimulated Emission Computed Tomography (NSECT). In this new type of computed tomography, the photon emission is stimulated by the inelastic scattering reaction from the nuclei of stable isotopes and fast neutrons. In this paper we will discuss the feasibility of the use of a AmBe sealed source for the production of fast neutrons, while considering the efficiency related to the isotropy of emission, the optimized shielding and fast neutrons collimation.

## 1. INTRODUCTION

The emission computed tomography stimulated by fast neutrons (NSECT) intend to provide an elemental spectrum of the body or part of the body being interrogated at each voxel of a three-dimensional computed tomographic image by using neutrons as the incident particle.

The acquirement of NSECT images uses a gamma spectrometer to capture the characteristic gammas rays that are produced in the inelastic collisions of scattering neutrons. The NSECT image reconstruction uses a neutron beam which illuminates a region of interesting, allowing the tomographic reconstruction. These images represent the spatial distribution of elements within the sample [1,2].

Due to the stochastic nature of photon emission process by irradiated tissue, one of the most suitable algorithms for tomographic reconstruction is the Expectation-Maximization (E-M) algorithm [3]. According to the algorithm formulation are considered simultaneously the photons emission and detection probabilities and these features make this approach one of the most relevant applications of the E-M algorithm.

According to the literature, the NSECT technique uses a neutron beam produced by d-d or d-t reactions. It will be proposed a moderation setup of an AmBe sealed source and its employment for acquirement of both tomographic reconstruction and gamma spectrometry. The neutrons spectrum moderation is necessary once the inelastic scattering reaction has an optimal energy range and the AmBe source spectrum has since thermal up to fast neutrons. In

addition, the AmBe already produces gamma rays and the moderation process releases capture gamma rays, therefore we will model a proper shielding for these undesirable gamma rays, since that were not produced by inelastic scattering in the sample.

## 2. METHODOLOGY

### 2.1. NSECT

The base of NSECT is the inelastic neutron scattering. This interaction happens when a beam of fast neutrons stimulates the stable nuclei in a sample, emitting characteristic gamma radiation. The photon energy produced is unique and is used to identify the emitting nuclei. All the energy produced composes the gamma spectrum, which can be used for tomographic reconstruction and spectroscopy of the elements distribution in the sample acquired through a non-invasive *in-vivo* scan [5]. In order to reproduce this tomography technique, a sealed neutron source of AmBe was virtually simulated with Monte Carlo Method (MCM) assuming all the physical radiation transport.

The Monte Carlo Method it's a statistical method, which uses a sequence of random numbers to perform a simulation. The simulation occurs with a high number of particles travelling through matter, colliding individually. The Monte Carlo method calculates macroscopic quantities of these particles, such as flux, or particle density [6]. The expected value of these quantities corresponds to the deterministic solution of the Boltzman equation. Specific quantities such as deposited energy or dose are derived from these quantities.

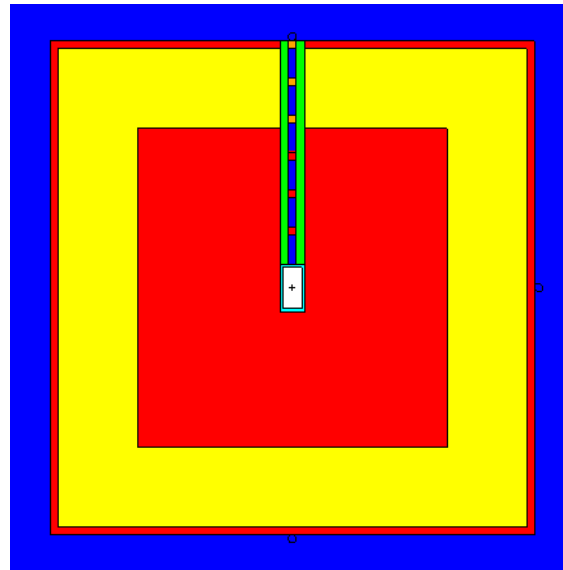
The MCNP code is well-know and widely used Monte Carlo code for neutron, photon, and electron transport simulation [7]. Since the mid-1970s (when the code was created) the code is being used for a lot of researches. The first code was created to simulated neutron and photon transport. Through the years the code has been modified, and it has been implemented generalized sources and tallies, electron physics, and coupled electron-photon calculations, macrobody geometry, statistical convergence tests and other features. In this work it was utilized the MCNP5, and we have entered all the information needed to run the simulation. We've entered with the geometry modeling, source specifications, material compositions, and the specific quantities to be calculated.

#### 2.1.1. Simulated system

The evaluated experiment was divided in two parts, the first one is related to neutron beam moderation and collimation and the second part represents the tomographic reconstruction. The AmBe spectrum was adopted according to the PTB standard [8]. The neutron source was modeled as a 6 cm height and 1.5 cm radius cylinder, and it is located in the center of the system. In front of the source we have modeled the collimator, where the neutrons will leave the system with direction to the target. The collimator consist in a corridor of 3x28 cm, the same diameter as the source, but the space that the neutron will pass has 0.5 cm radius, and around this corridor there is copper, which has 1 cm of thickness. In the corridor will pass through 6 barriers, the first 3 are a 1 cm thickness barrier of polyethylene and the final 3 are a 1 thickness barrier of beryllium, every barrier is spaced 3.666 cm from it other.

Around the source and the collimator, we have used polyethylene to block every neutron, so we have displayed this with 19.5 cm radius from the center, and 40 cm of thickness. Around

the polyethylene we've placed a 10 cm thickness of lead. Besides the system is completed, we have placed another layer, of polyethylene, to ensure that none neutron leaves the system, less the ones who leaves through the collimator. To test if the system is efficient or not, we created 3 sphere of air of 0.5 cm radius. One is located in the end of the corridor of collimation, the second is located in the opposite position, in the end of external polyethylene, the third is located in the end of the external polyethylene, but on the right side of the cylinder. The Figure 1 exemplifies the moderation and collimation setups.

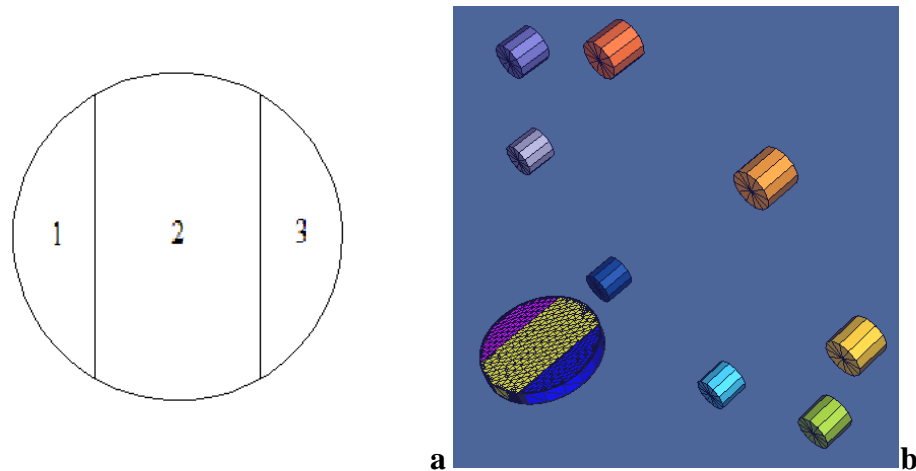


**Figure 1. Collimation of AmBe neutron source and moderation setup using polyethylene.**

The collimation objective is to have a neutron beam unidirectional propagation. Adopting this concept, the NSECT reconstruction is facilitate because of direction and the number of neutrons that reaches the detection system. If the incidents neutrons are unidirectional the neutrons loss in different directions is minimal, so the efficiency is higher. To have a good accuracy of photons detections, the number of neutrons must be in the range of  $3.21 \times 10^7$  [7]. If we have a system which the neutrons are unidirectional we can reach the range faster causing fewer doses in the subjective of study. The importance of this concept is that we can have a system that just block the undesirable neutrons, and the beam is multi directional, but, this can cause a higher dose and a loss of accuracy in the image, and if you spend more time to reach the range is uncomfortable to the patient.

With the constructed source system we have modeled the tomographic system. This system is basically a sample of three elements and eight detectors that were modeled as cylinders of 10 cm diameter and 9 cm height. The sample is a cylinder that contains 3 elements, aluminum (Al, located to the right side of the cylinder), copper (Cu, located at the center of the cylinder) and iron (Fe, located to the left side of the cylinder). The detectors are of high-purity germanium (HPGe), and they are located 45 degrees from each other forming a shape-ring detection of 80 cm diameter and displaced 60 cm from the center of CT field of view (FOV).

The source/detection system is then rotated slightly and a set of counts is obtained from the track particle transport in detectors during a translation past sample. This process is repeated once for each projection angle. The Figure 2 exemplifies the tomographic system.



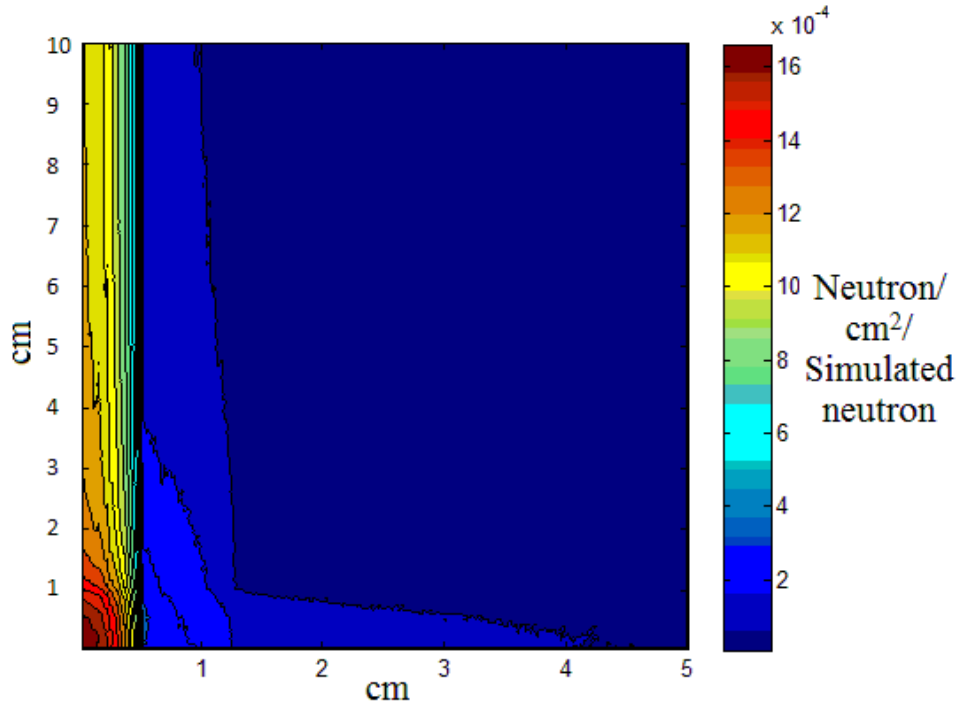
**Figure 2. Tomographic system: a) irradiated sample composed by aluminum (3), cooper (2) and iron (1); b) shape-ring detection system.**

The simulated sinogram was obtained considering 5975 neutron beam projections where it was performed 239 translations on 25 equidistant angular positions from 0 to 360 degrees. Due to excessive cpu time, it was not possible to stimulate the sinogram in high sampling rate, thereby some level of aliasing is expected on reconstruction.

### 3. RESULTS AND DISCUSSION

Given that one aim of the work was to analyze the feasibility of using an AmBe sealed source for the technique NSECT, we had to modify the neutron emission spectrum in order to eliminate high-energy and thermal neutrons. In addition, besides modify the spectrum we had to moderate fast neutrons. Based on the methodology proposed earlier simulations were made.

Through a previously acquired spectrum [8], it was necessary to moderate the fast component of the original spectrum in an attempt to restrict the neutron energies according to the cross sections of inelastic scattering. Associated to this task also is required a neutron shielding in order to suppress or eliminate the neutrons and photons leakage. The Figure 3 shows how the neutron flux within the system behaves.



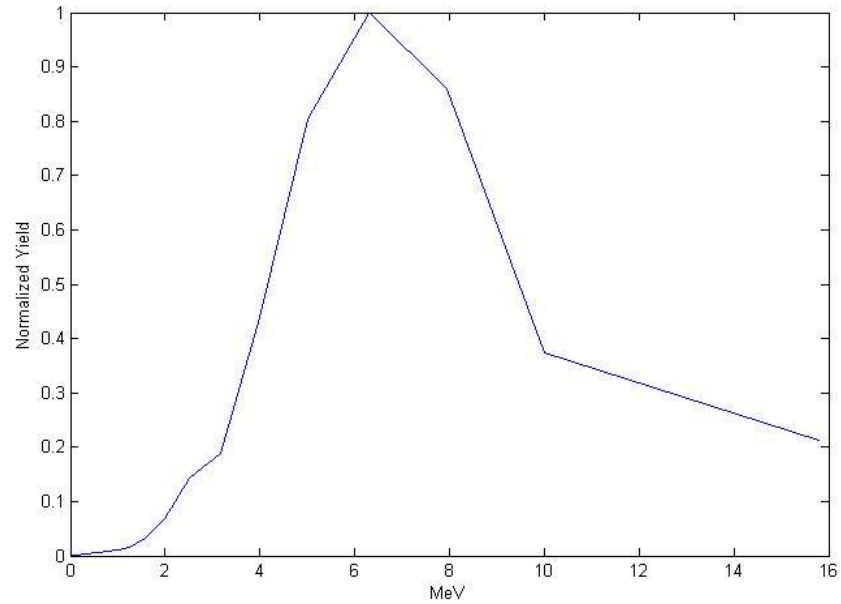
**Figure 3. Neutron flux inside of the moderation setup.**

The Figure 3 represents a small part of the moderation setup, but very important to this work, which is the source, the beginning of the polyethylene, and the collimation. The corridor where the neutrons must travel has 0.5 cm of radius as said earlier, in the figure shown above we see that in the first 0.5 cm the neutron flux is high, as we pass this 0.5 cm to the right, the flux decreases really fast, and goes approximately to zero after 4 cm. This result implies that the neutrons shielding is efficient, so the full system, which is not presented in the figure above, shield neutrons in unwanted direction, since this is an isotropic source. The same conclusion can be obtained through the flux estimation outside of moderation setup, which shows values close to zero.

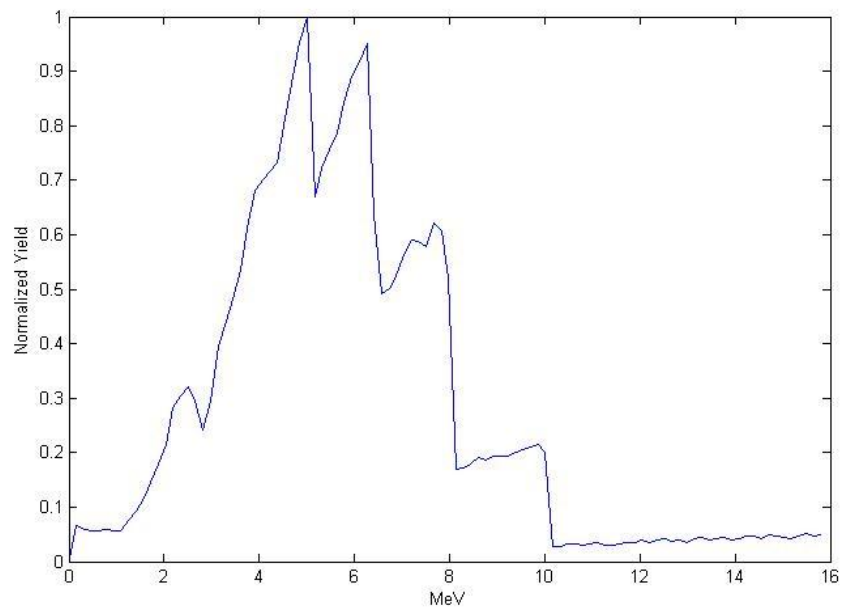
Analyzing the proposed collimation it is noticed that neutron flux remain straightforward. This means that the attempt to collimate the neutrons into the corridor was successful, and the flux decrease in this region is explained by the interactions that neutrons suffers through the corridor, but, even flux decreasing in 10 cm stays a little higher than half of the flux in the exit of the source.

Through some changes in geometry, we conclude that the best geometry was presented in the previous topic of the paper. The main objective of this geometric construction is the neutrons moderation considering an isotropic propagation. With the correct geometry we can go for the spectrum moderation one it is the most important parts of this work. Without this constraint has been done correctly through eliminating unwanted energies, there is no way to enable the use of an AmBe neutron source for NSECT technique.

Looking at the graphics below we can analyze the original spectrum of the AmBe neutron source (Figure 4) without any modification, and we can still analyze the graphic with the necessary changes that occurred due to the collimation setup (Figure 5).



**Figure 4. Original spectrum of AmBe neutron source.**



**Figure 5. Modified spectrum of AmBe neutron source.**

This result was obtained with the combination of the collimation cylinders of polyethylene and beryllium. The polyethylene was used to moderate the neutrons and beryllium is a metal reflector, which will cause a deceleration and a reflection of neutrons. Through 3 layers of polyethylene followed by three layers of beryllium, and between them being that there is an air space, it was possible to achieve the goal.

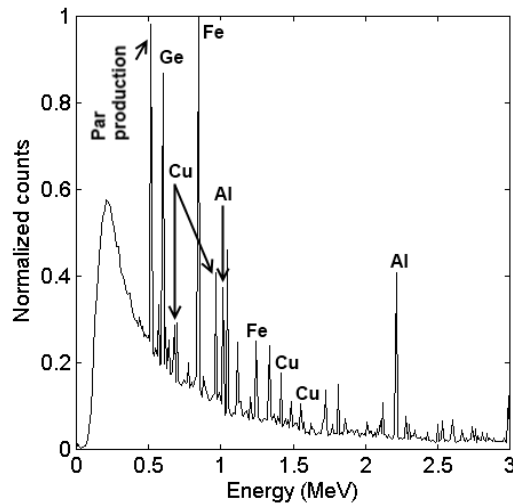
As the used source is not monoenergetic, it is necessary the moderation of neutrons to use in the experiment. Another factor which implies an unwanted neutrons shielding is the fact that the source does not emit neutrons in a single direction, so there must be an appropriate treatment in relation to the geometry so there are no neutrons in any direction other than we desire.

Remembering also that a source of AmBe produces gamma and that there is more production during the process of interactions throughout the system, it is necessary perform an analysis to see the amount of photons leaving the collimator toward the target in relation the number of neutrons that go toward the target. If the number of photons is relatively large in relation to the amount of neutrons will be necessary to adopt measures to block these photons

To make this comparison we analyzed the neutron and photon fluxes leaving the system toward the target, and made a simple math count to find the proportion of neutrons compared to photons. Done this calculation, we find that photon flux comprise about 1.13% of the number of neutron flux. To ensure that none neutrons of the isotropic source is gone leave the system, it was created three spheres, one in the end the corridor, and the other two right after the end of the external polyethylene. By looking at the flux in the two spheres after the external polyethylene and comparing to the sphere in the end of the corridor, we see that the flux in these spheres are so close to zero that are negligible. So the leakage can approximate to zero.

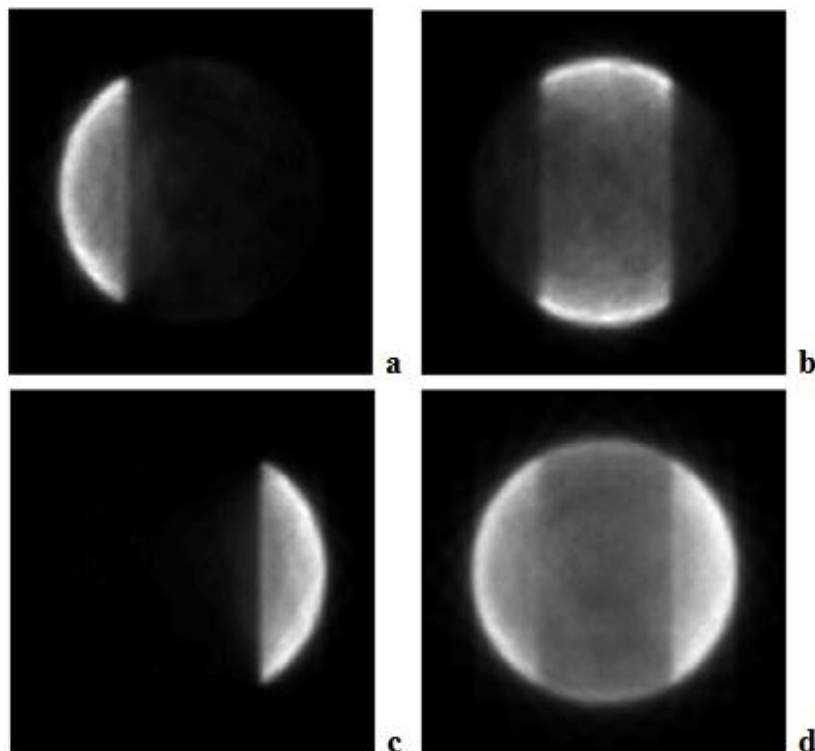
It is worth of mentioning that this geometry was the best fit for our goals and that there may be other types of geometric constructions that have equivalent or better results than the one shown. But among the geometries tested this was the one that could eliminate the thermal and fast neutrons, prevailing epithermal neutrons.

The second part of the proposed work compromise the tomographic reconstruction using the modified neutron spectrum. According to the inelastic scattering reaction, the photon emission is intrinsic to the emitting isotopes through specific energy levels. This feature can be seen on the emitted gamma spectrum shown on Figure 6. This spectrum presents peaks related to each element used in the target. Through these peaks is possible to perform image reconstruction. How does each element have specific peaks, we can analyze the spectrum to see how that is the distribution of elements, and if the energy acquired (represented by the peaks) are representing what we would like to see.



**Figure 6. Gamma emission spectrum.**

As can be seen in the presented spectrum, the peaks which represent each element can be identified. The counting record of these peaks is used to perform individual tomographic reconstructions. In other words, in the same counting acquisition it is possible to reconstruct the spatial distribution of each isotope individually or the whole sample. The Figure 7 shows the performed tomographic reconstructions.



**Figure 7. Tomographic reconstructions: (a) iron, (b) copper, (c) aluminum and (d) whole sample.**

Above lies the four reconstructions made, the first one represented by the letter (a) is the reconstruction of the iron, followed by the reconstruction of copper (b) and aluminum (c). The last reconstruction (d) was performed using all the elements together. We see in this figure that there was a predominance of the aluminum, but we can distinguish the three elements, which is an important fact. As we are talking of the NSECT technique, it's necessary that we can see differences between the elements, so that we can enable the NSECT.

There is no sense to calculate the absorbed dose in metallic samples but, according to literature [1], the absorbed dose related to the NSECT technique can be associated to x-ray CT scans in appropriate conditions, i.e. neutron flux, exposure time, number of detectors.

#### **4. CONCLUSIONS**

In view of the objectives proposed earlier, we can reconstruct a sample image using the NSECT technique with an AmBe neutron source. Such neutron source is not monoenergetic, and then there is the need to moderate the neutron spectrum. Not only the neutrons must be moderated and shielded, but during the collision process there is photon emission. It is necessary for the experiment to work properly such that photon flux must be lower than neutron flux.

For the objective of unwanted neutrons shielding the experiment proved to be satisfactory from the point that the neutron flux is restricted within the moderation setup. Knowing that is extremely important that there is no neutron flux out of the system towards undesirable directions.

One important point that we've worked is that must be no photons and neutrons leakage in the external part of the shield. By the techniques used we were able to reach this objective, certified by the flux in the spheres around the system, which was zero, less the sphere in the exit of the collimation corridor which has given a value of 1.13% for photons compared to the neutron flux.

The reconstructions made showed that AmBe neutron source has potential application for NSECT technique. The original spectrum was moderate to achieve an optimal energy range according to the inelastic scattering reaction cross section of the elements of interest. The reconstructed images showed the metallic samples individually and all of them together, which exemplifies one of the main features of the NSECT technique. In an experimental approach, it would be possible to perform the tomographic reconstruction with a portable neutron source which is easier to handle and cheaper if compared with commercial neutron generators.

#### **ACKNOWLEDGMENTS**

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