Counting System for the Carbon Activation Diagnostic

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Abstract

Multi-step nuclear reactions in the core of an OMEGA implosion can be used to infer the density of the deuterium-tritium (DT) fuel at peak compression, an important measure of the implosion performance. A three-step process leads to the production of tertiary neutrons with energies up to 30 million electron volts (MeV), more than twice the energy of the primary neutrons (14.1 MeV) from the direct fusion of DT[1]. The tertiary-to-primary neutron yield can be measured using a neutron-induced reaction on ^{12}C that is energetically not possible at the primary neutron energy. The (n, 2n) activation reaction on ^{12}C leads to the production of ^{11}C, which is unstable and has a half-life of 20.3 minutes[1]. The ^{11}C decays to ^{11}B and emits a positron (the antimatter equivalent of an electron) and a neutrino. The positron immediately annihilates with a neighboring electron, in the process emitting two 511-keV (thousand electron volts) gamma rays in opposite directions. LLE is developing a high-counting-efficiency detector system (in collaboration with the SUNY Geneseo physics department) to measure the number of activated ^{12}C atoms in a sample of graphite exposed to the tertiary neutron flux on the OMEGA laser. As part of this development process, measurements were made of the background sensitivity of the detectors to determine the shielding requirements. Counting efficiency in normal and Compton coincidence modes was explored. The first activated Cu-diamond mixture to be used for an absolute calibration of detector sensitivity was also part of this project.

1. Introduction

In an inertial confinement fusion (ICF) implosion, multiple nuclear reactions occur that lead to the creation of high energy neutrons with energy up to 30 MeV. Three reactions occur in an ICF implosion, as shown in Figure 1.1.

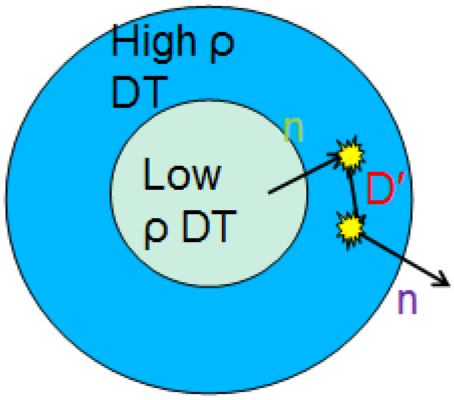


Figure 1.1
Three step process that creates tertiary neutrons. Primary neutrons are produced in the primary fusion reaction with 14.1 MeV energy. These may interact with a deuteron, transferring energy. If this energetic secondary deuteron fuses with a triton, the resulting tertiary neutron can have up to 30 MeV energy. This reaction takes place in the dense DT shell surrounding the low density, high temperature central region where fusion is initiated.

In the initial reaction, a deuterium atom fuses with a tritium atom to produce an alpha particle and a neutron with 14.1 MeV energy.

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n}\ (14.1\ \mathrm{MeV})$$

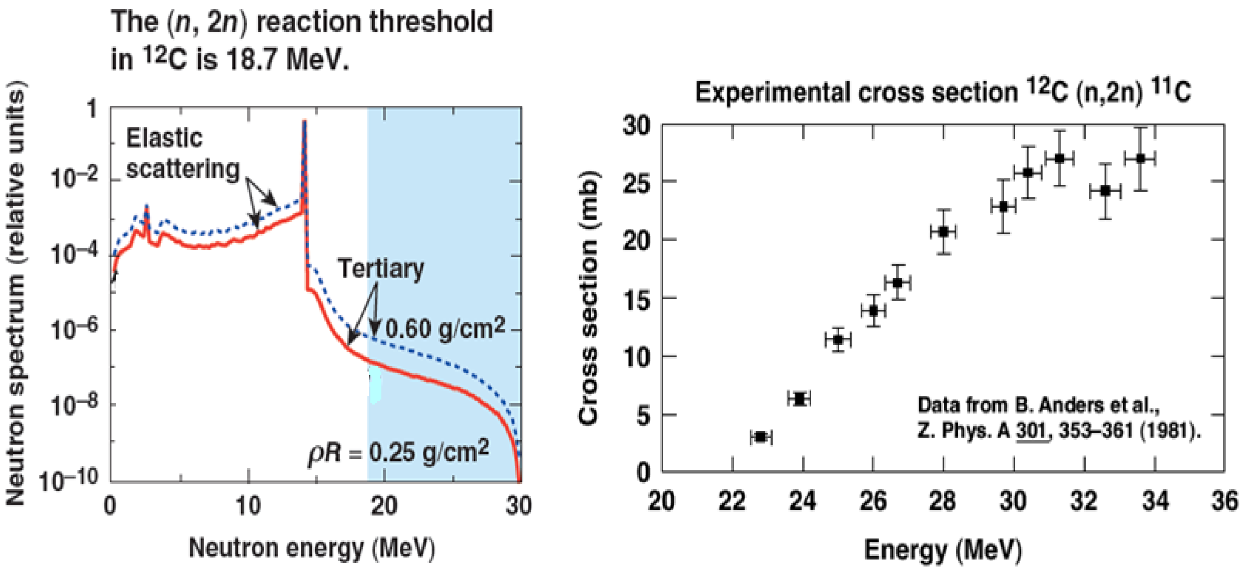
This primary neutron can then interact with another deuterium atom and transfer some of its energy, up to 12 MeV.

$$\mathrm{N}\ (14.1\ \mathrm{MeV}) + \mathrm{D} \rightarrow \mathrm{n}' + \mathrm{D}'\ (0\text{-}12\ \mathrm{MeV})$$

This energetic deuterium can then fuse with another tritium to produce another alpha particle and a tertiary neutron.

$$\mathrm{D}'\ (0\text{-}12\ \mathrm{MeV}) + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n}''\ (0\text{-}30\ \mathrm{MeV})$$

Because the probability of these reactions is related to fuel density, and there are two additional reactions necessary to produce a tertiary neutron, the ratio of tertiary neutrons to primary neutrons is proportional to the square of the fuel density.



(a) (b)

Figure 1.2
Simulated neutron spectrum from an ICF implosion and carbon cross section. (a) The blue area shows the energy that is only reached by tertiary neutrons, and the peak is the amount of primary neutrons. (b) This shows the energy needed for the (n,2n) activation reaction of ^{12}C, which is well into the tertiary range.

One goal of experiments at LLE is to achieve a fuel areal density (ρR) of 0.20 g/cm^2, but the current diagnostics for DT fuel are unable to measure densities this high. Carbon activation can be used to solve this problem because only tertiary neutrons activate carbon (Figure 1.2b). The tertiary neutrons are only produced by the reactions described, and there are a million times fewer tertiary neutrons than primary neutrons, as Figure 1.2a shows. By counting the gamma rays produced using a system of known sensitivity, the number of ^{11}C can be calculated, which leads to the number of ^{12}C activated and then the number of tertiary neutrons. The number of primary neutrons, which is needed to find the ratio, is measured by other diagnostics. Ultimately, the National Ignition Facility (NIF) will use the neutron activation system to measure ρR up to 2.0 g/cm^2. With a ρR of 0.20 g/cm^2, OMEGA is an appropriate place to test the diagnostic.

The prototype counting system for carbon activation has been set up and consists of detectors, electronics, and a computer program for data acquisition and analysis. Sodium iodide scintillators are arranged in a face centered cubic array to cover as much of the solid angle coming from the source as possible. When a gamma ray from the source hits the detector, the energy deposited is converted to visible light, which is further converted to an electrical pulse by a photomultiplier tube (PMT) attached to the detector. This signal is then amplified and shaped in a preamplifier and amplifier. Next, the signal is sent to an analog-to-digital converter (ADC), which takes the pulse and changes it to numbers that can be understood by the computer[2]. The computer program, called MPANT, records all of the signals as the ^{11}C decays and produces a spectrum for each detector consisting of the number of counts as a function of the initial gamma ray energy. Plots can also be made of counts over time and coincidence counts.

2. Background

Background radiation is the natural radiation that exists everywhere. It mostly comes from space, but it can also come from radioactive materials in the surrounding area, like ^{40}K in concrete walls or floors. Understanding the background is important because the number of ^{11}C produced by tertiary neutrons on OMEGA will be comparable to the signal from the background. This background needs to be understood so that it can be subtracted from the carbon signal for more accurate measurement of the tertiary yield. As Figure 2.1 shows, even when the detectors are completely shielded by lead, the background contributes a significant number of counts per minute, especially relative to the counts that would be expected from a carbon source.

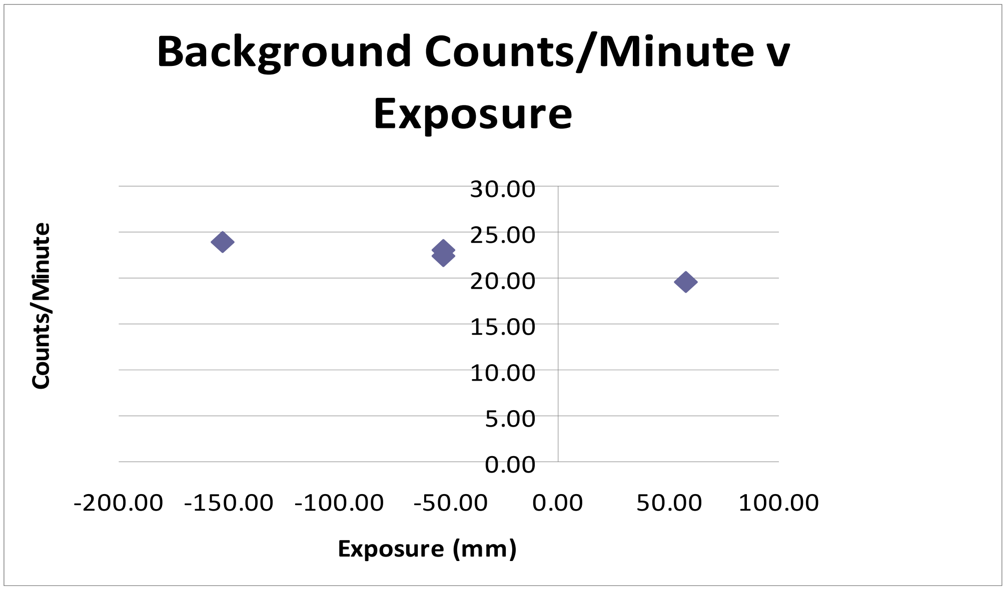


Figure 2.1
511-keV counts for one detector as a function of the exposure. A negative exposure means that part of the detector was not covered while a positive exposure means that the detector was completely covered.

Lead shielding is used to reduce the background signal that gets to the detectors, so tests were conducted to determine the optimal amount of shielding. This proved to be difficult with the detectors on the top and the bottom because it would require lead to be stacked vertically, but a new design is being developed to fix this problem. Tests with three detectors were run to see how the background signal changed with the addition of more lead. Both counts (Figure 2.1) and variation (Figure 2.2) were plotted against exposure, which is how much of the detector was covered by lead, measured from the end of the detector to the edge of the last piece of lead on top. A negative exposure means that the lead did not fully cover the detector and a positive exposure means that the lead extended past the end of the detector. A detector with an exposure of 58 mm had a background rate of 19.6 counts per minute in the 511 keV energy range, but the rate for this same detector when the exposure was -153 mm was 24.0 counts per minute. The standard deviation of the background rate also was lowered by the addition of more lead, from 39.97 when the exposure was -52 mm to 24.84 with a 58 mm exposure. Based on these results, a new design is being developed for the system to get the best possible coverage in terms of shielding detectors equally and using enough shielding.

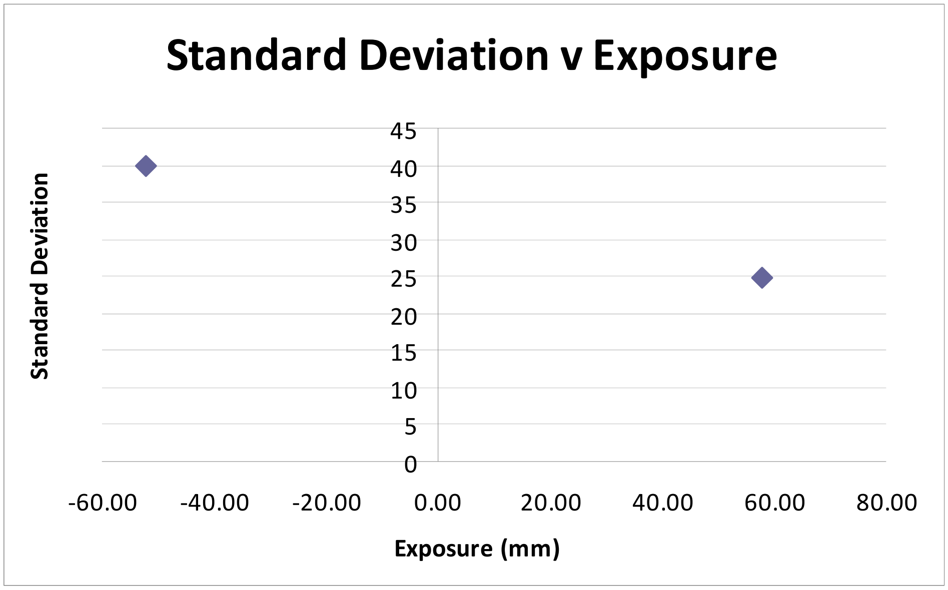


Figure 2.2
Standard deviation of 511-keV counts as a function of exposure.

3. Counting Efficiency

A coincidence count is defined as two detectors recording a signal at the same time. Coincidences are important because the positron emitted when a ^{11}C decays to a ^{11}B produces two back-to-back 511 keV gamma rays. Both of these gamma rays need to be identified because if there was only one, it could have easily come from space. The standard method for counting coincidences has been counting only the 511 keV coincidences, but the efficiency of this method is low. Both 511 keV gamma rays need to be detected for a positive identification, but they may not both arrive at the detectors with their full energy. After a gamma ray has been emitted from the source, it is possible that it will interact with an electron and lose some of its energy in a process called Compton scattering. This gamma ray will no longer have 511 keV, but it is still part of the signal and can be used to improve the signal-to-background ratio.

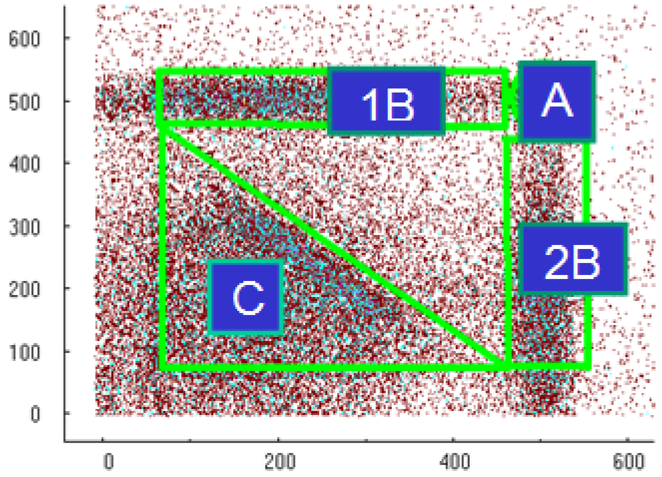


Figure 3.1
Energy recorded in detector 1 (keV) v energy detected in detector 2 (keV). Area A shows 511-511 keV coincidences, areas 1B and 2B show 511-Compton coincidences, and area C shows the Compton-Compton coincidences.

To capture as many counts as possible, coincidences are counted when both detectors register a 511 keV gamma, when one registers a 511 keV gamma and the other registers a Compton ray, and when both detectors record a Compton gamma ray. This is illustrated in Figure 3.1, which shows the area used for counting each of the different types of coincidences. The background levels are measured prior to the experiment and can be subtracted from the recorded counts. This is done by finding the average background counts per minute and multiplying by the time the experiment ran to get the expected counts for a certain amount of time. Once the background is subtracted, the process of calculating the counting efficiency can begin.

The experiment described here was done using ^{64}Cu that was activated by being exposed to the DT neutron flux on the OMEGA laser. The copper was placed at a distance of 40 cm from the center of the target chamber and was allowed to cool off for four and a half hours before counting to prevent saturation of the detectors. Before the sample was placed in the counting system, it was mixed with diamond powder until it was evenly distributed and then placed in a container. Diamond powder was used to simulate graphite because solid graphite has the same density as diamond powder and the signal attenuation would be as close as possible to the same in both. Graphite will be the ultimate activation sample used for the operational diagnostic, so it was important to get similar results from the tests. The first step in measuring the counting efficiency is finding the activation ratio, A_r, which is how many activated atoms are produced per source neutron. This ratio is given by Equation 1[3]:

$$A_r = n_s * t_s * \sigma_s * \Omega \tag{1}$$

where n_s is density of the source in atoms per cubic centimeter, t_s is the thickness of the source, σ_s is the cross section, and Ω is the solid angle. Once this ratio is known, the number of total decays expected can be calculated using Equation 2[3]:

$$CC = A_r * C_{eff} * Y_r * Y_p B_r \tag{2}$$

The total decays expected, CC, is the product of the activation ratio, A_r, the counting efficiency, C_{eff}, the tertiary to primary yield ratio, Y_r, the primary neutron yield, Y_p, and the branching ratio, B_r, which is the fraction that decays by positron emission. This equation can be used to determine the total *counts* expected if the counting efficiency is known, but if not, it can be used to calculate the total *decays* expected by assuming that the counting efficiency is 100%. This number will then be used to find the actual counting efficiency.

The counting efficiency is simply the fraction of the expected decays that were actually measured. Because of equipment problems, the experiment using activated copper was conducted with only three operational detectors instead of six. As shown in Figure 3.2, two detectors were set up across from each other (1B and 2B) and one detector was placed at a right angle to both (2A). Figure 3.2 shows this arrangement. Counts are considered a signal if they are located in the 511-511 range, either 511-Compton range, or the Compton-Compton range. The average of the counts from the right angle spectra, which were 1B with 2A and 2B with 2A, was multiplied by four to give the number of counts that would be expected for a detector with all four detectors at right angles operational. This number was added to the back-to-back counts to get the total counts for one detector. A background measurement was taken prior to this experiment and the background rate in counts per minute was calculated for each of the four regions that were counted (the regions are shown in Figure 3.1). This rate was then multiplied by the number of minutes the copper experiment ran and subtracted from the total counts to give the total measured signal counts for the experiment.

The number of expected decays for the experiment was calculated using the total decays expected and the nuclear decay equation. This equation can be used to determine the counts expected at the beginning of the experiment and the counts remaining at the end of the experiment. The difference is the amount of decays expected for the time the experiment was run. To get the counting efficiency, C_{eff}, Equation 3 can be used:

$$C_{\text{eff}} = \text{counts recorded} / \text{expected decays} \tag{3}$$

The counting efficiency for this system came out to be 9.9% based on the experiment done with the copper.

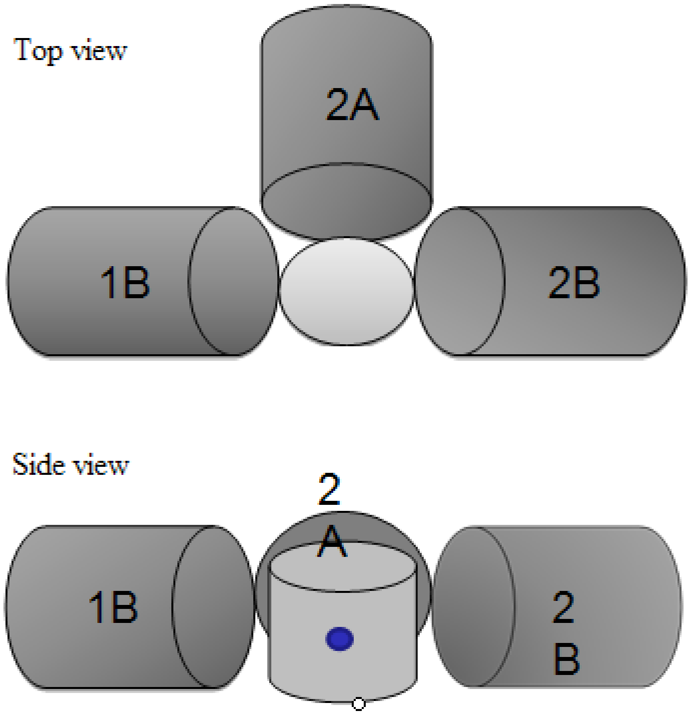


Figure 3.2
Top and side views of detector setup. The light gray cylinder in the middle is the diamond powder, with the blue dot in the middle representing the source. The source was actually distributed throughout the diamond to more closely simulate the eventual graphite source.

4. Conclusions

This project helped to advance the development of a key diagnostic for the OMEGA laser. Background studies confirmed that all detectors should be shielded as evenly as possible to make it easier to separate signal counts from background radiation. Experiments using copper and diamond powder were done to determine the counting efficiency of the system, which will be important when carbon is used as the source.

Ultimately, the carbon activation diagnostic will be used by the NIF to measure the density at the center of their ICF implosions.

5. Acknowledgements

I would like to thank my advisor Dr. Craig Sangster and Tim Duffy for their help and patience throughout the project. Dr. Padalino and his students Cassie Brown and Melissa Cummings, from SUNY Geneseo, were very helpful when I was first learning how the system works. Finally, I would like to thank Dr. Stephen Craxton for running the high school program and for giving me a chance to participate.

6. References

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(2) Knoll, Glenn. Radiation Detection and Measurement. First edition. John Wiley & Sons, 1979.

(3) LLE PDM# D-ES-X-157 Rev B: Omega Tertiary Activation Diagnostic Engineering Optimization Study. 23 Sept. 2007.