Inferring a Neutron Yield from Nuclear Activation Techniques

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I. Abstract

Nuclear measurements are essential for studying inertial-confinement-fusion experiments when plasmas reach the conditions necessary for generating fusion reactions. One approach to inferring a nuclear yield is to measure the time integrated yield from the neutron-producing deuterium-deuterium (DD) fusion reaction with neutron-induced activation of indium isotopes. In this method, a neutron yield can be calculated based on the gamma ray spectrum that results from the deexcitation of indium-115. 336 keV gamma rays, from the reaction channel ^{115}In (n,n')^{115}In, were counted using a high-purity germanium (HPGe) detector. A second DD fusion reaction with an equal branching ratio produces a proton yield, which was used to determine a cross-calibration factor (*f*) for the HPGe detector. The proton yield measurements were generated from a joint campaign between LLE and MIT on March 3rd, 2020. The gamma ray counts were post-processed in MATLAB along with proton yields to generate an *f* value. This value was used to generate net indium yield values as the emitted gamma ray count is proportional to the nuclear yield. These yields were then verified in the Omega Nuclear database. A distinct lower limit was set on the nuclear yield for each neutron time-of-flight detector to ensure accurate calculations and detector measurement uncertainty was determined to be less than one percent for the HPGe diagnostic.

II. Introduction

Fusion reactions create the most fundamental form of energy of the universe. Thermonuclear fusion occurs when nuclei from atoms with low atomic weight, such as hydrogen, bond to form a nucleus that has a higher atomic weight, such as helium. This process leads to the release of energy in the form of high-energy particles that are emitted when the total mass before the reaction exceeds the resulting mass of the system ($E = Mc^2$). Every star, including our sun, utilizes the process of thermonuclear fusion to form energy. Stars and the Sun can naturally generate fusion reactions due to their significantly large masses, which allow them to gravitationally compress the gas in their cores. As this compression occurs, their cores reach extremely high temperatures (the temperature of the center of the sun is 14 million degrees Celsius) and densities, which causes nuclear fusion to ensue.[1]

The OMEGA laser at the Laboratory for Laser Energetics (LLE) is used to compress the fuel within a target so that it achieves very intense temperatures and densities creating the foundation for research in high energy conditions, similar to those that occur in the sun. The fusion reactions are triggered by temperatures reaching several tens of millions of degrees Celsius, which are significantly greater than those reached by the sun.

Scientists believe that fusion energy will be that of the future due to its vast amount of positive factors. Nuclear fusion is a practically inexhaustible source of energy, it is operated in a contained environment, and it does not release radioactive material into the atmosphere. Additionally, fusion does not contribute to greenhouse gas emissions due to its ability to function without a gas or oil source.[1]

There are two approaches to setting up a fusion reaction: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF). Nuclear fusion utilizes a plasma, which is produced when hydrogen gas is heated to extremely high temperatures and the positively charged nuclei are separated from the negatively charged electrons. Electric charges have the ability to interact with magnetic fields, allowing them to guide the direction of the plasma. The magnetic fields in MCF prevent the plasma from contacting the walls of the reactor, which would dissipate a fraction of the system's energy. The most effective MCF model takes on a toroidal shape. The system's helical magnetic field lines control and confine the plasma.[2]

The OMEGA laser conducts direct drive fusion reactions as shown in figure 1. A target is accelerated by utilizing incident laser beams that directly irradiate the target. Newton's third law states that every action has an equal and opposite reaction. Therefore, a rocket effect occurs as the laser beams heat then ablate the outside of the target, which causes the target's plastic shell to blast outward, generating an outer layer of plasma. This forces the inner portion of the target to implode. The example shown in figure 1 illustrates a target containing deuterium and tritium fuel that is imploded. The outer portion of the target is ablated, creating a central hotspot in the fuel core and plasma. This differs from indirect drive implosions, which irradiate a target through x-rays generated by incident laser beams that irradiate the inside of a symmetric cylindrical case (known as a hohlraum) containing the target. Both produce an environment created by the outer plasma which heats the fuel to densities and temperatures that allow for thermonuclear fusion reactions to occur. If enough of the alpha particle energy produced by the fusion reaction is deposited in the fuel to heat more fuel to fusion temperatures, thermonuclear burning takes place.

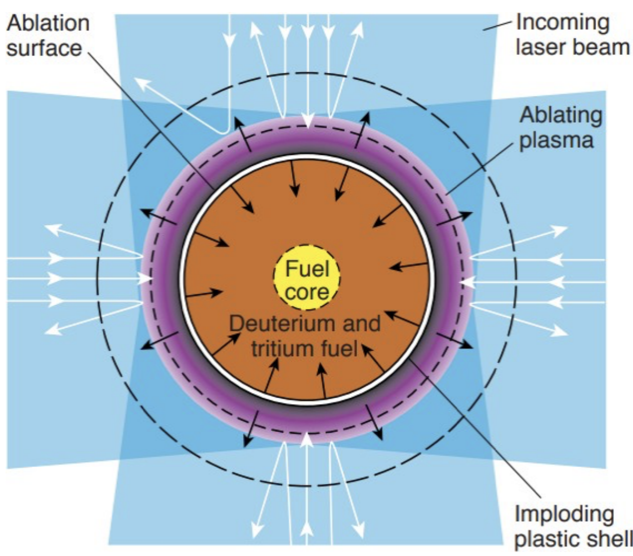


Figure 1: *Demonstration of the direct drive fusion process. Ablating material accelerates the fuel, and the resulting force compresses the reaction inwards. This process creates the temperatures and densities necessary for fusion reactions to take place.*[1]

Once thermonuclear burning ensues, the plasma core will continue to burn and produce energy until the core's pressure and temperature are not able to sustain further fusion. Newton's First Law of Motion states that an object will remain either at a constant velocity or at rest until acted upon by an external force. This is how the inertia of the fuel causes it to remain compressed in the core of the target. This fuel burns and produces energy until the system reaches a pressure high enough to degrade the implosion, causing the shell to rapidly expand. Fusion reactions appear instantaneous, as the compressed state in which they occur lasts for less than one billionth of a second, which is the only time that useful energy is generated during the reaction.[1]

Isotopes of hydrogen, deuterium and tritium, are universally used to conduct fusion reactions due to their high cross sections. A list of known cross sections for such reactions are listed in table 1 (taken from Ref. 3).

Table 1: *Deuterium-Tritium Reaction Channels*

Reaction			σ_{max} (barn)	E_{max} (keV)
D + T	→	^{4}He (3.5 MeV) + n (14.1 MeV)	5.0	64
D + D	→	T (1.01 MeV) + p (3.03 MeV)	0.096	1250
	→	^{3}He (0.82 MeV) + n (2.45 MeV)	0.11	1750
D + ^{3}He	→	^{4}He (3.6 MeV) + p (14.7 MeV)	0.9	250
T + T	→	^{4}He (0-3.5 MeV) + 2n (0 - 9.4 MeV)	0.16	1000
	→	^{5}He (1.7 MeV) + n (8.7 MeV)		
	→	^{5}He* (~4.4 MeV) + n (~6.0 MeV)		
^{3}He + ^{3}He	→	^{4}He + 2p (12.9 MeV)	0.12	8500
T + ^{3}He	→	^{4}He + n + p (12.9 MeV)	0.06	1075
	→	^{4}He (4.8 MeV) + D (9.5 MeV)		

* implies excited state.

σ_{max} is the maximum cross-section σ for a reaction where σ represents the area around one interacting particle that the other reacting particle must hit in units of barn (10^{-24} cm^2), which is correlated to the probability that the reaction will occur. E_{max} is the maximum energy in units of kiloelectron-volts in the center of mass frame at which the cross section σ is maximum (with a value of σ_{max}). As demonstrated by the large cross-section, DT reactions have the highest cross section and occur more frequently than DD fusion reactions. The specific DD cross section that will be further explored in this project results in the formation of a helium-3 atom and the emission of a neutron.

The goal of this research was to calibrate a DD-n Indium-115 yield detector. In order to measure the number of neutrons emitted in the DD reaction, a neutron activation approach was taken. Indium activation is the process of activating a sample of Indium-115 through its interaction with high-energy neutrons generated from a fusion reaction, producing an unstable nuclear state.[3] The decay reaction of the activated indium sample produces gamma rays that can be counted by detectors to determine the neutron yield. This is important because inferring primary yields using the activation approach is an effective method for cross-calibrating other detectors for accurate yield measurements.

Neutron yields are calculated by first using the gross counts measured from gamma ray spectra. Net counts are then found by subtracting the background from the gross counts. This was made possible on March 3rd, 2020, when LLE and MIT ran a joint campaign to produce a calibrated Indium-115 detector for DD neutrons. This paper focuses on the outcomes of this collaboration.

III. Experimental

Indium-115 was chosen to measure DD neutrons due to its well known half life decay and emission of 336 keV gamma rays. As shown in figure 2, Indium-115 has a half-life of 4.49 hours (269 minutes). This half life is advantageous because it allows for indium samples to be transported from the chamber to a high purity germanium (HPGe) detector where 336 keV gamma rays are counted.[4] In comparison, other elements, such as Copper-63 with a half-life of 9.74 minutes, decay much faster and cause accurate yield measurements to become harder to achieve.

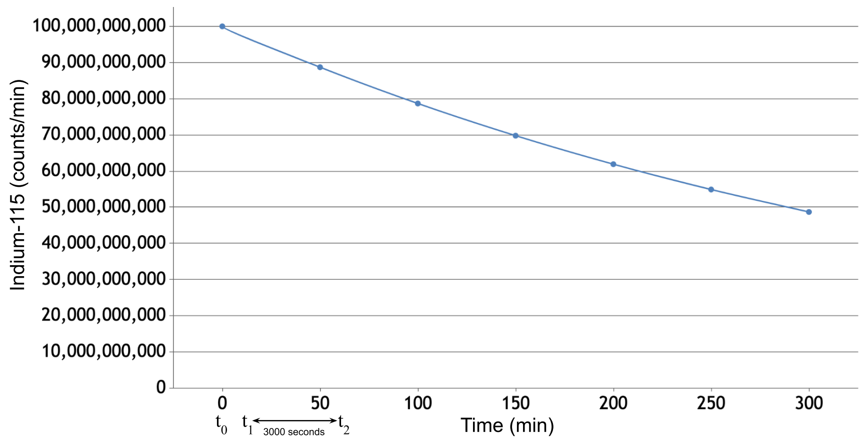


Figure 2: *Indium-115 decay curve that demonstrates gamma ray counts as a function of time and illustrates the sample's half life. t_0, t_1, and t_2 are labeled on the x-axis to show the time taken to transfer the indium sample to the counting chamber (t_1) and the counting time (t_2).*

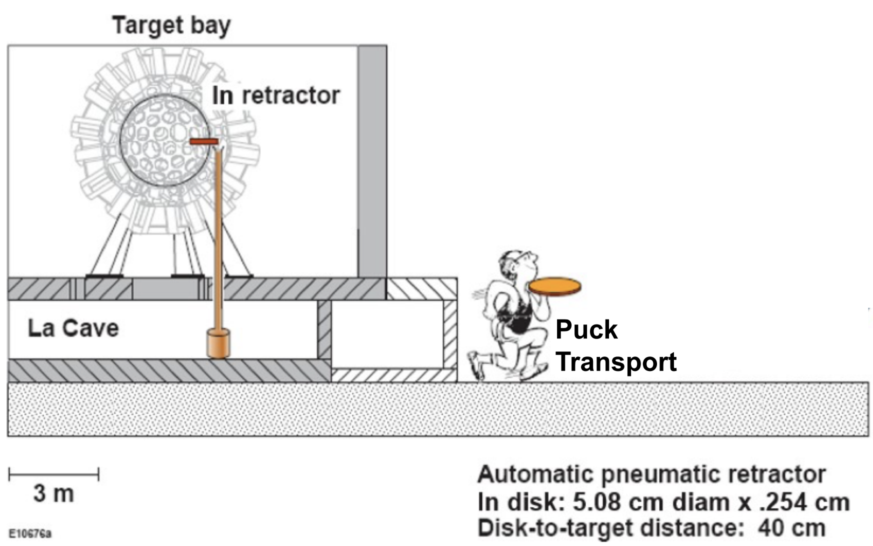


Figure 3: *A visualization of the transportation process for indium activation that illustrates the target chamber. It is required for a person to physically move the indium puck from the chamber to the counting facility, where an HPGe detector can count the gamma rays emitted from the indium.*[5]

The In-activation system depicted in figure 3 contains a target that is irradiated by laser beams positioned symmetrically around it. The target is a plastic shell filled with deuterium and tritium at cryogenic temperatures. In this experiment, an indium sample and germanium detector were selected to measure the neutron yield through gamma ray counts. The Indium-115 sample, which was a 0.254 cm thick by 2.54 cm radius cylinder puck, was placed at a mean distance of 40 cm from the neutron source. An indium retractor was used to remove the activated indium puck from the target bay after the fusion reaction occurred. The indium samples were then transferred to a counting facility where counting occurred using HPGe detectors for 3000 seconds. The intensity of the 336 keV gamma ray decay could be concluded from the counts achieved.

By using known distances between the target chamber center and detector, neutron time-of-flight (nTOF) detectors were also used to measure the energy spectrum of neutrons emitted from the target. nTOF detectors at distances of 12 meters, 5.4 meters, and 3 meters were used in order to measure neutron yields from the reaction. Each detector has different ranges of sensitivity that produce valid yield measurements until saturation is reached. This results in an inability to accurately measure the contribution to the yield from low-energy neutrons (those below the lower bound set on the nTOF detectors), which hinders the detector's ability to formulate absolute yields for all D-D and D-T reactions. As shown in table 2, the 3 meter detector has the lowest saturation point at about 1E+10 neutrons onto the detector, so it is not viable for indium activation shots. The 5 meter and 12 meter detectors are more accurate nTOF detectors for indium activation due to their higher saturation points of 3.616E+10 and 3.215E+10, respectively.

Table 2: *Saturation points of nTOF detectors for measuring DD neutrons*

nTOF Detector	**Saturation Point**
3m nTOF	Saturated at 1E+10; below a majority of indium activation shot yields
5m nTOF	3.616E+10
12m nTOF	3.215E+10

There are several challenges to overcome when conducting these ICF experiments that had to be considered when calculating the yield from the measurements. These challenges may reduce neutron yields and lead to inaccurate calculations when yields are, in reality, higher than what is measured. Significant challenges include non-uniformity in the fuel target and variations in the laser beam energy deposition on the target. Non-uniform laser beams that are incident on the target create Rayleigh-Taylor instabilities. As the implosion progresses, this instability grows due to a surrounding lower density plasma pushing against the higher density fuel. When the imploding fuel shell decelerates as it approaches the target center, the deceleration Rayleigh-Taylor instability occurs. This causes perturbations–as shown in figure 4–that reduce the resulting target's neutron yield.[6]

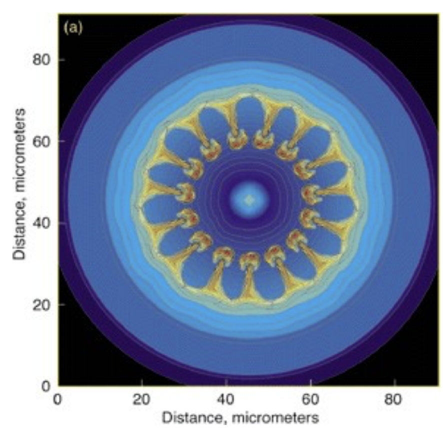


Figure 4: *Visual representation of the density contours and vorticity that arise from penetration of inner fuels as the outer shell pushes lighter fluid.*[6] *This creates deceleration instabilities that can reduce the efficiency of nuclear measurements.*

Oftentimes, predictions of experimental results overestimate an ICF system's performance by neglecting how non-uniformities in the target degrade the yield. Roughness of the inner surface also leads to target perturbations. LLE has achieved a greater laser uniformity through the use of smoothing by spectral dispersion.[7] Measuring the neutrons from fusion reactions will aid in understanding these instabilities and how to mitigate them.

IV. Data Analysis

This MIT and LLE joint campaign generated data from 12 shots that were used to produce a calibrated Indium-115 detector for DD neutrons by comparing DD-p and DD-n detectors, which measure proton and neutron yields, respectively, for each shot, and calculating an average calibration value. The neutron and proton branching ratio for DD fusion reactions are equal, so equivalent yield values generated by MIT's DD-p detector and LLE's DD-n detector are expected.

A consistency check was performed to verify how Gamma Vision,[8] an application used for HPGe spectrum analysis, calculated the net counts and uncertainty of gamma rays for each shot. The Gamma Vision formulas listed below were processed in MATLAB and net counts as well as error bars were calculated for all the indium activated nuclear fusion shots taken at the lab. Figure 5 displays a visual of the variables calculated and used in the formulas.

The first formula used was B = $\left(\sum_{i=l}^{l+(n-1)} Ci + \sum_{i=h-(n-1)}^{h} Ci \right) \frac{h-l+1}{2n}$ which calculates the background by calculating the average counts of the channels surrounding the region of interest (ROI) where l is the low limit channel, h is the high limit channel, and Ci is the counts of channel

i. The second formula used was $An = \sum_{i=l+n}^{h-n} Ci - B$ which calculates the net counts of the peak An by subtracting the calculated background from the adjusted gross area where the adjusted gross area, Aag, is the sum of all the channels in the ROI that are not used in the background from l+n to h-n. The third formula used was $\sigma_{An} = \sqrt{Aag + B(\frac{h-l-(2n-1)}{2n})(\frac{h-l-(2n-1)}{h-l+1})}$ which calculates the uncertainty in the net counts of the peak.[8]

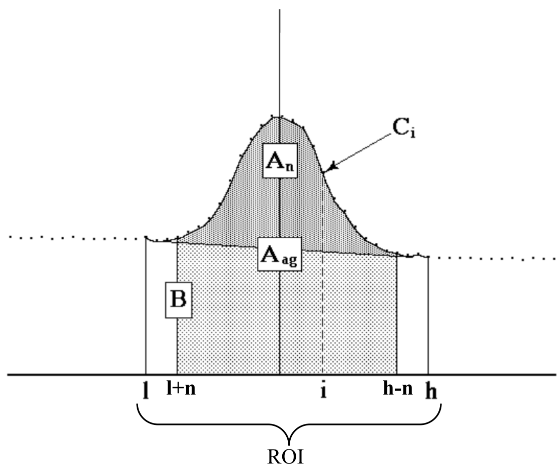
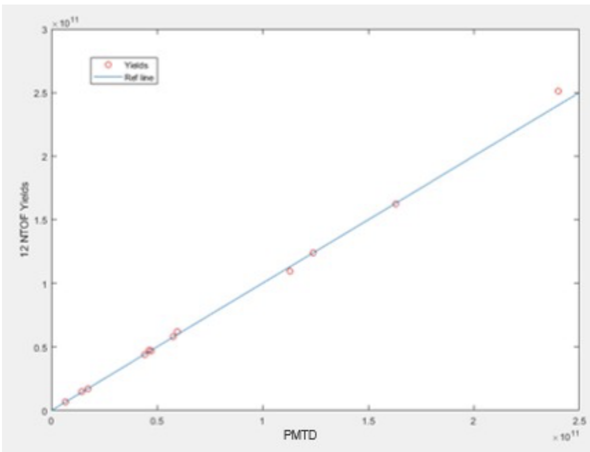
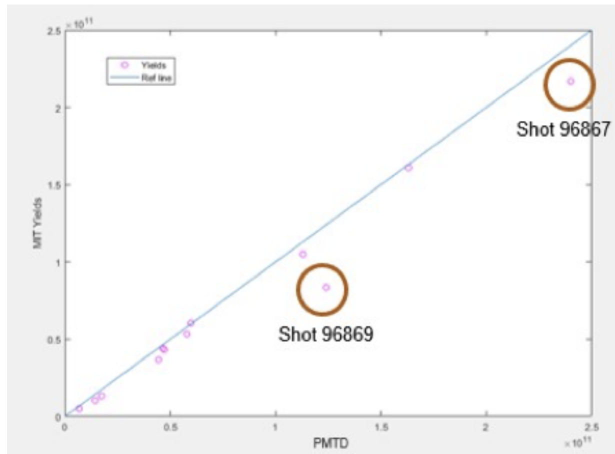


Figure 5: *Net counts were calculated by subtracting the background from gross counts. The diagram shows the specific components used to calculate and separate the background from the net counts. n is the number of background points selected to calculate the background. n−1 points on each side of the peak form the endpoints of the straight-line background. The x axis represents the energy spectrum and the y axis represents gamma ray counts* [8]

Figure 6 shows plots of the 12 meter neutron time-of-flight detector's (12 nTOF) yield and MIT's DD-p yield against the yield from a photomultiplier tube detector (PMTD), which is an excellent device for determining DD implosion yields due to its high precision and accurate ion-temperature measurements.[9] This plot demonstrates that the PMTD and nTOF detectors strongly agree, validating their respective yields, which illuminates two clear outlying points. A linear relationship was visible between the PMTD and the 12 meter nTOF detector, and the two outlying points were clear when plotted against the PMTD (circled in red in figure 6), further providing evidence for an inaccurate DD-p MIT yield measurement from two of the shots.



(a) PMTD yields vs. 12m nTOF yields



(b) PMTD yields vs. MIT yields

Figure 6: *The PMTD yields plotted against (a) the 12 nTOF yields and (b) the MIT DD-p yields. The blue lines are y = x, which demonstrates the agreement between the yields plotted on the axes as they fall very close to the blue lines. Thus, these plots clearly show the two outlying MIT yields as they deviate from linearity.*

After removing the two outlying points, the cross calibration factor (*f*) used to accurately measure DD fusion neutrons was calculated using the formula shown below

$$f = \frac{l'^{2}_{s}(An)}{N l_{s}^{2}(e^{-\lambda t_1} - e^{-\lambda t_2})M_{in}}$$

where l_s is the mean distance from the neutron source to the indium sample (l'_s refers to the parameters from pulsed neutron yields), An represents the net counts of the peak, N is the neutron yield, λ is the inverse mean lifetime of Indium-115, t_1 is the delay time between neutron irradiation and counting, t_2 is the counting time, and M_{in} is the mass of the Indium-115 sample.[10] The 10 remaining MIT dd-p yields, discarding the two outliers, were used as N and a corresponding f value was calculated for each shot. These values were then averaged together to generate an average f value of $3.78\mathrm{x}10^{-8}$. The average f value was used in the formula in place of f, and the formula was rearranged to calculate a cross calibrated neutron yield value for the 140 DD-n LLE shots.

To further verify a higher accuracy after the two outlying points were removed, the DD-n yield value for each shot was generated using a calibration factor calculated from all 12 DD-p MIT shots and then with the two outlying points removed. The two sets of neutron yields calculated using the differing calibration factors were then plotted against the 12 nTOF detector. With all shots used for calibration, a 0.739% standard error was observed. After the outlying points were removed, a slightly lower standard error of 0.736% was observed, which supports the removal of the inaccurate shots in the cross calibration calculation.

This calibration factor *f* was then used to cross calibrate indium detector gamma ray spectra. The background was removed from the gamma ray counts and the net counts from 140 nuclear shots were calculated and plotted in figure 7. The formulas used in this process were coded in Matlab to create a neutron yield calculator.

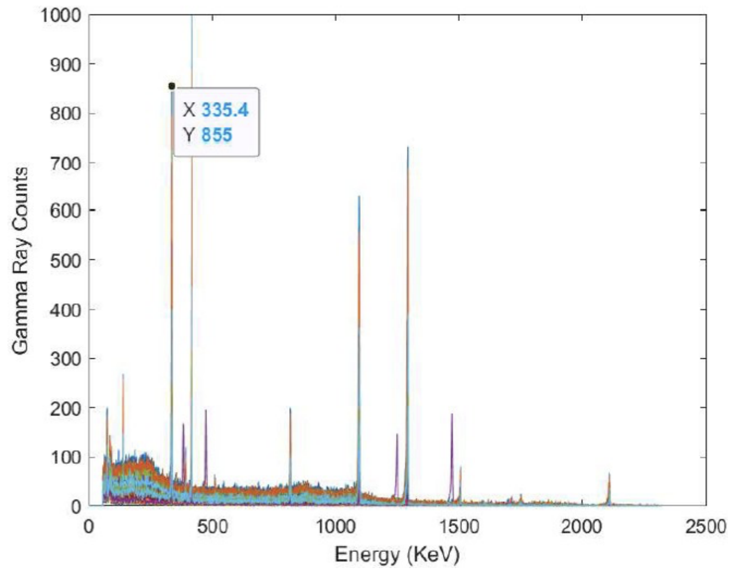


Figure 7: *Gamma ray counts generated from 140 overlaid nuclear shots taken with the OMEGA laser. The peak studied in this experiment was the 336 keV peak. The gamma rays generated from each shot were calibrated using a MATLAB neutron yield calculator to calculate nuclear yields that were verified in the Omega Nuclear database. This graph demonstrates other count peaks that were not further investigated but have potential to be studied in the future.*

VI. SUMMARY AND SUGGESTIONS FOR FUTURE WORK

A DD-n Indium-115 Yield detector was calibrated during a joint campaign between LLE and the MIT Plasma Science and Fusion Center. 140 nuclear shots were run through a MATLAB calculator to produce neutron yield measurements that were added to the Omega Nuclear Database. Two suspect DD-p MIT points were removed from calculations of the calibration factor *f*. By removing the two outlying points, the standard error between the DD-n yields plotted against the 12 meter nTOF yields decreased, verifying a more accurate calibration factor without the two MIT points. A lower bound was set for each nTOF detector to guarantee accurate nuclear yield measurements by examining deviations in linearity against the current indium yields in the Omega Nuclear Database.

As seen in figure 7, there are other reaction channel peaks that could be further researched such as the 417 or 1097 keV peaks. Data gathered from these reaction channels could further confirm the current DD-n indium yield values. Additionally, it is currently assumed that the D-D reaction leads to two product branches that are evenly split, where 50% of the time, protons are released and the other 50%, neutrons are released. By using the DD-p MIT yields and the DD-n LLE yields, this theory could either be confirmed or contradicted.

One may also consider the effects of altering the experimental setup, for example, the size of the puck that is irradiated by the laser. The puck size in this experiment was chosen due to readily available 0.254 cm thick by 2.54 cm radius cylindrical pucks. However, there is potential for experimentation with larger pucks. A larger puck would allow for lower yields and higher counts to be measured. With the puck size used in this experiment, yield measurements were limited by a lower bound of approximately 3E+10. Conversely, the puck size must not exceed the detector's ability to count every gamma ray emitted by the sample, setting an upper bound for the maximum size of the sample. By creating a MATLAB code to calculate the optimal size for the puck that does not exceed the upper limit, future work can produce more accurate yields as the lower bound would decrease, capturing gamma ray counts that may be missed with the current indium sample size.

VII. Acknowledgements

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