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The NIF Total Neutron Yield Diagnostic*

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ABSTRACT

We have designed a total neutron yield diagnostic for NIF which is based on the activation of In and Cu samples. The particular approach that we have chosen to use is the "calibration factor" method in which we calibrate the entire counting system. In this method, In and/or Cu samples are exposed to known sources of DD and DT neutrons. The activated samples are then counted with the appropriate system: an HPGe detector for In and a NaI coincidence system for Cu. We can then calculate a calibration factor, which relates measured activity to total neutron yield. The advantage of this approach is that specific knowledge of such factors as cross sections and detector efficiencies are not needed. The disadvantage is that it may be difficult to mock-up in a calibration experiment the actual scattering environment of NIF. As a result, the experimentally obtained calibration factor may have to be modified using the results of a numerical simulation of the scattering environment. In this paper, the calibration factor methodology will be discussed and experimental results for the calibration factors will be presented.

INTRODUCTION

The National Ignition Facility (NIF) is a laser fusion device designed to drive an inertial confinement fusion (ICF) target to ignition, producing a significant fusion yield.[1] Measurement of the total neutron production will be a primary diagnostic. Nuclear activation[2] techniques have traditionally been used in inertial confinement fusion experiments to measure neutron yields above about 10^8 neutrons, while a more sensitive technique, plastic scintillation, must be used for lower yields.[2] The concept of nuclear activation detectors is simple: a suitable material is exposed to a neutron source, the induced activity

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measured, and then, knowing the activity induced per neutron incident on the sample, the total neutron yield can be estimated. In this paper we discuss the NIF Phase One total neutron diagnostic for measuring deuterium-deuterium (DD) reaction neutrons and deuterium-tritium (DT) reaction neutrons. To obtain the relationship between neutron yield and induced activation, we employ a detector system calibration method,[3-4] which we refer to as the "F factor" method.

Two of the most commonly used nuclear activation diagnostic materials for measuring DD and DT fusion neutrons are indium and copper, respectively. Indium is used to measure the 2.45 MeV neutrons from the $^{2}H(d,n)^{3}He$ reaction via the inelastic neutron scattering reaction with In-115: $^{115}In(n,n')^{115m}In$. This reaction has a threshold of 336 keV. The In-115m metastable state has a half-life of 4.49 hours and emits a 336 keV gamma ray. Copper is used to measure the 14.1 MeV neutrons from the $^{3}H(d,n)^{4}He$ reaction via the reaction: $^{63}Cu(n,2n)^{62}Cu(\beta+)$. This reaction has a threshold of 11 MeV. The half-life of Cu-62 is 9.74 minutes. Although Cu-62 does emit a few gamma rays, their branching ratios are very low (< 1%), so it is generally detected by measuring the 511 keV positron annihilation gamma rays.

Another reaction also takes place with copper: $^{65}Cu(n,2n)^{64}Cu(\beta+)$. This reaction has a threshold of 10 MeV. The half-life of Cu-64 is 12.7 hours and, like Cu-62, is a positron emitter. This reaction cannot be used as a diagnostic reaction because Cu-64 is also formed when Cu-63 captures a neutron. At high yields, the background produced by the long-lived activity of Cu-64 can become high enough that it prevents a good measurement of the Cu-62 activity, which places an upper limit on the yields that can effectively be measured with copper. As a result, Phase Two total neutron yield diagnostics, as discussed by Barnes[5], are being developed for high-yield NIF operations, which will use alternative reactions.[6]

There are two basic approaches to "calibrating" an activation diagnostic system: that is, determining the amount of activity induced in a sample per incident neutron. One approach is to use fundamental quantities, including the reaction cross section leading to activation and detector efficiency, to calculate the system response as

discussed by Barnes.[5-6] The other approach is the F factor[3-4] method in which an entire system (sample geometry, detector, electronics) is calibrated, which eliminates the need to know most fundamental quantities. In this paper we first describe the methodology of the F factor technique. We then briefly describe the calibration experiments we have conducted and report on the results of these experiments. Finally, we describe the limits of this diagnostic for measuring neutron yields on NIF.

METHODOLOGY

In the F factor method, an entire detector system is calibrated and then the same system is used to measure unknown neutron yields. Let us first consider the theory of the calibration procedure, which will yield a calibration factor, F, having units of counts per neutron per unit area per gram of sample. As an example, let us consider the specific reaction for measuring DD neutrons, $^{115}In(n,n')^{115m}In$, and note that the procedure for calibrating any other reaction will be analogous.

First an appropriately sized indium sample is exposed to a known neutron flux, which for most calibrations, will be a steady-state neutron source. In this case, the number of In-115m metastable nuclides, N(t), produced as a function of irradiation time, t, is given by

$$N(t) = R(1 - e^{-\lambda t})/\lambda \qquad (1)$$

where R is the reaction rate of In-115m and λ is the decay constant of In-115m ($\lambda = 4.29 \times 10^{-5}$ s). This reaction rate can be written in terms of fundamental quantities:

$$R = \phi \varepsilon_A M N_A \sigma(E)/A_W \qquad (2)$$

where ϕ is the neutron flux in neutrons/cm^{2}s incident on the indium sample, ε_A is the natural abundance of the In-115 isotope (95.7%), M is the mass of the sample in grams, N_A is Avogadro's number, A_W is the atomic weight of indium (114.82), and $\sigma(E)$ is the cross section of the reaction in square centimeters. Thus, the total number of In-115m metastable states, N_o, present at the end of an irradiation time, t_o, can be written as

$$N_o = \phi \varepsilon_A M N_A \sigma(E)(1 - e^{-\lambda t_o})/\lambda A_W \qquad (3)$$

The decay of the In-115m metastable state can be detected by measuring the 336 keV gamma ray. This radiation is most readily detected with a high-purity Ge detector (HPGe). The number of decays of In-115m over the time interval from t_1 to t_2 measured from the end of irradiation is given by integrating dN/dt over that time interval. The number of 336 keV counts that will be recorded by the detector as a result of these decays is given by multiplying the number of In-115m decays by the detector efficiency, ε_D; the branching ratio for emitting the 336 keV gamma ray, ε_B (45.8%); and a factor that accounts for the self-absorption of the 336 keV gamma rays within the sample, ε_S. The net number of 336 keV gamma rays recorded by the detector is equal to the total peak-area count, C, minus the background count, B. Thus, we get

$$(C - B) = \phi\varepsilon_A\varepsilon_D\varepsilon_S\varepsilon_B M N_A \sigma(E)$$

$$x\,[(1 - e^{-\lambda to})(e^{-\lambda\, t1} - e^{-\lambda t2})]/\lambda A_w \qquad (4)$$

Now assuming a point source of neutrons that emits S neutrons per second, we can write the neutron flux as

$$\phi = S/4\pi d^2 = Y/t_o 4\pi d^2 \qquad (5)$$

where d is the distance between the neutron source and the indium sample and Y is the total neutron yield assuming an isotropic yield. Substituting this expression for the flux into Eq. (4) and rearranging we can define a calibration factor, F, in terms of experimental quantities:

$$F = (C - B)t_o\,(4\pi d^2)\lambda/YM(1 - e^{-\lambda to})(e^{-\lambda\, t1} - e^{-\lambda t2}), \qquad (6)$$

or, alternatively, in terms of fundamental quantities:

$$F = \varepsilon_A\varepsilon_D\varepsilon_S\varepsilon_B\sigma(E)\, N_A/A_w \qquad (7)$$

Note that the F factor "contains" the reaction cross section, the detector efficiency, and the sample self-absorption factor but does not require explicit knowledge of these quantities. Rather, we determine the F factor from easily measured experimental quantities: the neutron yield, the irradiation and counting times, and the distance between the neutron source and indium sample.

For application to NIF or other short pulsed experiments, the quantity $(1 - e^{-\lambda t_o})$ can be approximated by λt_o and we can rewrite the F factor as:

$$F = (C - B)(4\pi d^2)/YM(e^{-\lambda\, t1} - e^{-\lambda t2}) \qquad (8)$$

Since the F factor is already known from a calibration experiment, we can readily determine the total neutron yield on an application such as NIF by using Eq. (8):

$$Y = (C - B)(4\pi d^2)/FM(e^{-\lambda\, t1} - e^{-\lambda t2}) \qquad (9)$$

This same basic approach is applicable to all reactions and detection systems. If specifics about the geometry of the application are known prior to calibration, these factors can also be included in the F factor calibration. For example, if there will be a 2.5 cm-thick stainless steel flange between the indium sample and the fusion neutron source on NIF, then the system could be calibrated with such a flange in place. This calibration would eliminate the need to model the neutron attenuation and scattering through the flange.

It is our experience that the more parameters that can be "calibrated out" of the problem, the less chance there is for introducing errors into the result. A classic example of a potential source of error is the determination of the detection efficiency for counting annihilation gamma rays from a positron emitter. The only readily available positron emitting calibration standard is Na-22. There is a potential problem because Na-22 also emits a 1274 keV gamma ray with a 100% branching ratio. The 511 keV annihilation gamma rays and the 1274 keV gamma ray can be detected in coincidence, which leads to a summing of the two deposited energies within the detector. As a result, the coincident 511 keV gamma rays that should have been detected in the 511 keV, full-height peak are removed from that peak to a higher energy region of the spectrum. If not properly accounted for, the measurement of the activity of Cu-62, for example, will be in error, with the discrepancy being as much as a factor of two depending on detector/source geometry. In the F factor approach, however, copper (or other radionuclide of interest) is used directly to calibrate the system and effects, such as summing, are inherently included in the calibration. A dedicated Na-22 source would still be used to set the energy windows about the 511 keV peaks and check

coincidence rates to insure that the system is functioning properly.

CALIBRATION

The experimental technique we used to measure the calibration factors for indium for DD neutrons has been described in detail in an earlier paper.[3] Briefly, an electrostatic accelerator was used to generate a 175 keV deuterium beam, which was focused onto an ErD_2 target. In the initial experiments, nominal 5-gram indium samples were placed at 0° relative to the beam at distances of 10, 20 and 30 cm. At this angle the neutron energy was 3.0 MeV. The samples were exposed to neutrons for a measured amount of time. The induced sample activities were measured with a 30 % efficient HPGe detector. Samples were counted on the face of the detector and at distances of 5 and 10 cm from the face. The neutron yield was measured using the associated-particle technique.[7] Protons were counted from the $^2H(d,p)^3H$ reaction at an angle of 165°. The neutron fluence at the indium sample was then inferred from the charged particle count.

In the original experiments the accelerator target chamber design did not allow measurements at 95°, which is the angle at which the DD neutrons have the preferred calibration energy of 2.45 MeV. Thus, a new target chamber was designed to allow measurements at 95° and F factor calibrations were repeated. The irradiation of samples at 95° was the only significant change in the experimental design from the earlier work and the procedures remained essentially the same for the indium calibrations.[3]

In addition, we calibrated the copper reaction with DT neutrons in these subsequent experiments. In these experiments, an ErT_2 target was used and alpha particles from the $^3H(d,n)^4He$ reaction were measured and used to infer the neutron flux on the activation samples. The masses of the copper samples were nominally 6.2 grams. Samples were placed 10 cm from the source at an angle of 95° for which the neutron energy was 14.1 MeV. Irradiation times ranged from 900 to 1200 s. The annihilation gamma rays from the positron decay of Cu-62 were counted with a NaI coincidence system.[4] The samples were placed between two, 12.5 cm diameter by 7.5 cm

thick NaI scintillation detectors that were separated by 4 cm. Standard NIM coincidence electronics were employed. Multi-channel scaling was use to record the coincidence events as a function of time. The Cu-62 activity was then determined by subtracting the longer-lived Cu-64 activity using standard stripping techniques. The F factor in this case was based on the number of Cu-62 coincidence events recorded in a time interval t_1 to t_2, as measured from the end of irradiation.

The F factors that we obtained for the $^{115}In(n,n')^{115m}In$ reaction at a neutron energy of 2.45 MeV are 4.76×10^{-5} +/- 8%, 6.34×10^{-6} +/- 15%, and 2.5×10^{-6} +/- 20% counts/neutron per unit area/gram of indium for measurements on the detector face, and at 5 cm and 10 cm from the face, respectively. Samples were irradiated at various distances and the resulting F factors were all within the stated uncertainties, which indicates that scattering was not a significant issue in these experiments. For the copper reaction, only a single counting geometry was employed. The F factor that we obtained for the $^{63}Cu(n,2n)^{62}Cu(\beta+)$ reaction at a neutron energy of 14.1 MeV is 3.43×10^{-4} +/- 8% counts/neutron per unit area/gram of copper.

Although these experiments were designed to measure F factors, we can estimate the reaction cross sections if we know the detection efficiency and have an estimate of the sample self-absorption. Although our use of thick sample targets will limit the accuracy of these cross section measurements, it is worth calculating cross sections from our data because good agreement between the cross section values we obtain and accepted values will support the validity of our measurements. To estimate the $^{115}In(n,n')^{115m}In$ cross section, we used a calibrated, multi-line source and interpolated in energy to obtain an efficiency at 336 keV. Only data taken at 5 and 10 cm from the face were used to determine the cross section to minimize the differences in counting efficiencies between the "point" calibration source and the volumetric indium sources. The measured efficiencies for detecting 336 keV gamma rays at 5 and 10 cm are 0.0123 and 0.00484, respectively. The sample self-absorption of the 336 keV gamma was estimated by doing a Monte Carlo simulation and was found to be 0.696. For the copper measurements, we used a Na-22 source to measure the detector efficiency of the NaI coincident system and found it to be 0.165 +/-

20% after correcting for summing. The self-absorption of the 511 keV gamma rays was calculated to be 0.754.

The cross section for the $^{115}In(n,n')^{115m}In$ reaction was calculated to be 339 +/- 27 mb, which, within uncertainties, agrees with the ENDF/B-VI[8] value of 326 mb. The cross section for the $^{63}Cu(n,2n)^{62}Cu$ and $^{65}Cu(n,2n)^{64}Cu$ (F factor = 5.7×10^{-5} +/- 8%) reactions were determined to be 435 +/- 87 mb and 887 +/- 177 mb, respectively. Again, within the uncertainties, these values agree with ENDF/B-VI[8] values of 454 mb and 906 mb, respectively.

APPLICATION TO NIF

The fielding of this diagnostic on NIF has been discussed by Barnes.[3] In addition to the equipment Barnes lists, we require four high-efficiency, NaI coincidence counting systems.[4] Four detector systems are required to simultaneously count four, short-lived Cu-62 samples: the number of samples that could potentially be irradiated on a single shot. For experiments not requiring coincidence measurements, these NaI detectors could be dedicated to gamma ray counting as suggested by Barnes.[3]

In our standard design, the targets are nominally 2.5 cm in diameter and 1 cm thick, although the thickness can be reduced for measuring higher yields. For the standard sample size located a nominal 4 m from the inertial confinement fusion (ICF) target, the minimum DD yield that can be measured with indium is about 1.3×10^{12} neutrons. If it proves necessary to measure lower yields, the sample could be located closer to the target and, thereby, increase the sensitivity by a factor of $1/R^2$. The minimum allowable distance between the source and the sample on NIF will be 50 cm at which distance the minimum detectable yield decreases to 2×10^{10} neutrons. The mass could also be increased if necessary, which would increase the sensitivity approximately linearly with mass. Also, yields at least a factor of ten lower could be measured if a larger statistical uncertainty is acceptable. There is no serious upper limit on the yield that can be measured providing one is willing to address the problems due to high count rate by either delaying the count or by counting the samples at a greater distance from the detector.

Higher-yield DD measurements are complicated, however, by the fact that secondary DT reaction neutrons can also excite In-115 to the metastable state. It may be possible to separate the contributions of the two reactions, however, by using the fact that the 14.1 MeV neutrons of the DT also drive the reaction $^{115}In(n,2n)^{114m}In$ reaction, which has a 9.3 MeV threshold. This reaction could be used to determine the 14.1 MeV neutron yield, which could then be used to calculate the fraction of the In-115m activation due to 14.1 MeV neutrons. We have made preliminary measurements of the F factors for the $^{115}In(n,2n)^{114m}In$ and $^{115}In(n,n')^{115m}In$ reactions and found them to be approximately 4.6×10^{-5} and 1×10^{-5} counts per neutron per unit area/gram of copper, respectively, as measured on the face of the detector. In practice, the In-114m reaction may be too insensitive to measure secondary DT yields. Even if one accepts poor counting statistics and counts the sample for a day, the minimum DT yield that can be measured with the In-114m reaction at a source to sample distance of 50 cm is about 1×10^{11}. Thus, the copper reaction may have to be used to measure the secondary DT yield. We should also note that the ratio of DD to DT F factors for the In-115m reaction is 4.8, which agrees with the ratio of the respective reaction cross sections, 4.8, as theory would predict.

The copper activation samples will be counted with a NaI coincidence system. The NaI detectors will be 15 cm in diameter by 7.5 cm thick positioned 4 cm apart. For a standard 45 gram copper sample located 50 cm from the ICF target, the minimum DT neutron yield that can be measured is about 3×10^{10}, although this limit could be lowered by about a factor of ten if a larger statistical uncertainty is acceptable. The upper yield that can be measured is ultimately limited by a combination of Cu-64 (12.7 hour half-life) production and dead time effects in the detector. The actual limit is a complicated function of target mass and the decay time before the start of the count. If one uses a standard 45 gram sample located at 4 m and begins a 20-minute count, one minute after irradiation, the upper limit is only about 3×10^{15}. If one reduces the mass to 0.1 grams and keeps the same count interval, the upper limit increases to about 1×10^{18}. One can raise the upper limit for 0.1 gram samples to at least 10^{19} (the highest yield anticipated on NIF) by delaying the start of the count by one to two hours. At these high yields, however, the

length of counting times required may prove impractical. Thus, at high yields the copper reaction might best serve as a confirmation of the results obtained primarily with alternative reactions.[4]

CONCLUSION

We have calibrated the F factors for indium and copper nuclear activation diagnostics for measuring DD and DT fusion yields. The method is simple and "user friendly". This method is capable of measuring NIF start-up yields and with some minor variations could cover most of the range of anticipated NIF yields.

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