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Copper activation deuterium-tritium neutron yield measurements at the National Ignition Facility[a)]

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A DT neutron yield diagnostic based on the reactions, ^{63}Cu(n,2n)^{62}Cu(β^+) and ^{65}Cu(n,2n) ^{64} Cu(β^+), has been fielded at the National Ignition Facility (NIF). The induced copper activity is measured using a NaI γ-γ coincidence system. Uncertainties in the 14-MeV DT yield measurements are on the order of 7% to 8%. In addition to measuring yield, the ratio of activities induced in two, well-separated copper samples are used to measure the relative anisotropy of the fuel ρR to uncertainties as low as 5%. *© 2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4746999]

I. INTRODUCTION

A copper-activation, neutron yield diagnostic has been fielded on the National Ignition Facility (NIF).[1] Copper activation has been a standard diagnostic for measuring the 14.1 MeV neutron yields of DT fusion experiments for more than thirty years.[2] The primary diagnostic reaction of interest is ^{63}Cu(n,2n)^{62}Cu(β^+), which has a threshold of 11 MeV, making it relatively selective to DT neutrons. The ^{65}Cu(n,2n)^{64}Cu(β^+) reaction, which has a 10 MeV threshold, can also be used to measure DT yields but can suffer from interference from the ^{63}Cu(n,γ)^{64}Cu(β^+) reaction, which has no threshold. Cu-62 has the additional advantage of having a 9.673 m half-life versus a 12.7 h half-life for Cu-64, which makes it the more sensitive diagnostic reaction.

II. METHODOLOGY

The methodology used to measure a neutron yield has been discussed previously.[3,4] To summarize, for a short-pulse neutron source that is isotropic and induces radioactivity in a sample, we can determine the neutron yield above the reaction threshold from the relationship

$$Y = (C - B)(4\pi d^2)/Fm[\exp(-\lambda t_1) - \exp(-\lambda t_2)], \qquad (1)$$

where Y is the neutron yield, C is the total counts measured in the time interval t_1 to t_2 where time is measured from the end of the neutron pulse, B is the background during this time interval, m is the mass, λ is the decay constant of the induced radionuclide being measured, and d is the source to sample distance. With the exception of the parameter F and the known decay constant, these parameters are all determined at the time of the experiment.

The parameter "F" in Eq. (1) can be determined by measuring it directly in a calibration experiment in which the sample is exposed to a known neutron source.[3] Alternatively, F can be calculated from a combination of fundamental constants and knowledge of the efficiency for counting the radiation of interest and the effects of attenuation and scattering of the irradiation environment

$$F = \varepsilon_a \varepsilon_d \varepsilon_b \varepsilon_i \sigma(E) N_A / A_W. \qquad (2)$$

Here ε_a is the natural abundance of the target nuclide of interest, ε_b is the branching ratio for the emission of the radiation of interest, N_A is Avagadro's number, and A_W is atomic weight of the element being irradiated, $\sigma(E)$ is the energy dependent cross section,[5] which are all known. Of more concern is accounting for the source spectrum through the energy dependent cross section; determining the irradiation efficiency (ε_i) which accounts for all attenuation and scattering effects; and determining the absolute counting efficiency (ε_d) for measuring the copper activity. These concerns will all be addressed in this paper.

The NIF neutron sources will have spectra that depend upon the burn temperature and fuel ρR. For exploding pusher shots the spectra will be approximately Gaussian whereas cryogenic layered shots having a significant ρR will have a complex down-scattered component. We have used MCNP[6] to predict the induced copper activity for variety of source spectra including a monoenergetic 14.1 MeV source, standard Gaussian DT sources characterized by temperatures ranging from 1 to 15 keV, and for typical down-scattered spectra. The difference between predicted induced activity for

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the monoenergetic and standard Gaussian sources is small: 0.7 to 1.5% with largest difference being for a 1 keV temperature. The combination of the Gaussian-shaped spectra and raising neutron cross section accounts for these modest differences and agrees with previous work.[4] Unlike Gaussian spectra, down-scattered spectra are asymmetric and the differences in induced activity compared with an assumed 14.1 MeV monoenergetic source have been predicted to be as large as ∼10%, although to date actual measured differences have been smaller.[7] To obtain the most accurate *total* yield, the data should be analyzed using the actual source energy spectrum. Historically, however, inertial confinement fusion DT yields measured by activation diagnostics have generally assumed Gaussian energy distributions and necessarily only "count" source neutrons, unscattered or scattered, which have energies above the reaction threshold. The National Ignition Campaign adopted this latter approach for the reporting of activation diagnostic yields with the understanding that these yields will underestimate the true, total yield on shots having significant fuel ρR. To date this effect appears to be small and the yields reported by the three primary neutron yield diagnostics, Zr and Cu activation and the Magnetic Recoil Spectrometer (MRS), almost always agree within the error bars of the respective measurements.[7]

III. EXPERIMENT AND RESULTS

Since both ^{62}Cu and ^{64}Cu are positron emitters, we chose to measure the subsequent annihilation photons in coincidence, which allows us to measure induced activities to as low as ∼0.1 Bq. The detector is a NaI coincidence system which has been described by Leeper *et al.*[8] The two NaI detectors are 15.24 cm diameter by 7.6 cm thick NaI detectors and are separated by 4 cm. Standard Nuclear Instrument Module coincidence electronics are employed.[8] Multichannel scaling is used to record the number of coincidence events as a function of time and the samples are counted until an accurate measurement of the ^{64}Cu activity can be made. At the NIF the samples are counted for a minimum of 7.5 h.

We routinely field one primary copper sample located (see Fig. 1) on the NIF line-of-sight (LOS) located at the NIF Chamber (θ,φ) coordinates of (116,316) where $\theta = 0°$ is the top of the chamber. The 5.08 cm diameter by 0.1 cm thick copper sample (∼19 g) is mounted on the end of a collimator that penetrates an approximately 2-m thick, concrete biological shield wall and is 1900.5 cm from target chamber center (TCC). This sample resides in a room known as the Alcove and it has been designated NAD18A (for Nuclear Activation Diagnostic Alcove). The coincidence counting system is also located in the Alcove.

To reach the copper sample, the neutrons must first exit the evacuated target chamber through a 1.27 ± 0.026 cm thick Al 6061 port flange located 5 m from TCC and then pass through a 45-cm long stainless steel port collimator which defines the neutron beam diameter at the copper samples. At the exit of the port collimator is a 1.252 ± 0.002 cm thick tungsten x-ray shield. The remaining transport is through air to the copper sample except for a 0.05 cm aluminum plate covering the entrance to the wall collimator. We note that this geometry constitutes extremely "clean," narrow-beam geometry for the major scattering materials in the LOS and emulates the geometry used for total neutron cross section experiments.[9] Foster defines a geometrical inscattering index[9] which for our geometry is only $\sim 2.3 \times 10^{-5}$ which indicates significantly less inscattering than in the experiments of Foster. An MCNP ring detector calculation, although not strictly applicable for our geometry, confirms this conclusion since the calculated collided contribution to the total number of ^{62}Cu(n,2n) reactions is $< \sim 0.02\%$.

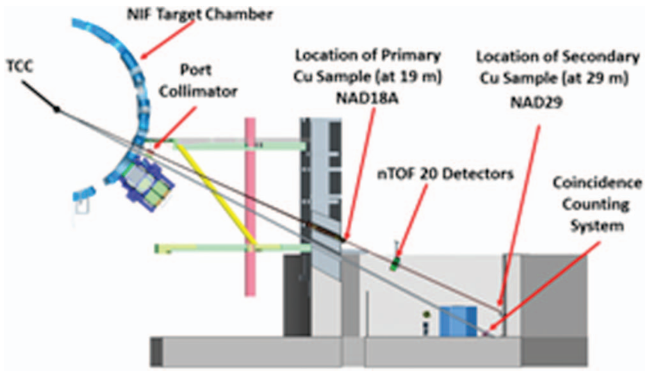

FIG. 1. The alcove LOS layout. The NAD18A sample is located 1900.5 cm from TCC. The NAD18E LOS exits horizontally and at an azimuth rotated 142° from the NAD18A LOS.

More recently we have also begun to field a second copper sample located on the NIF LOS (90,174) which is on the equator. This LOS configuration is identical to that of the Alcove except that this LOS penetrates the shield wall normally so the distance to the copper is only 1730.2 cm from TCC. This LOS is designated NAD18E (Equator).

The narrow-beam geometry of the two primary NAD18 samples means that our attenuation and scattering correction to the yield relies almost entirely on the total neutron cross section of the aluminum port cover and the tungsten shield. These cross sections are known to 1% to 2% accuracy.[5] The densities and thicknesses of the tungsten shields are known to tolerances of <0.2%. The Al 6061 port flanges were each thinned to a thickness of 1.27 cm with a tolerance of ±2%. Since it was not possible to do a confirmatory measurement of the actual thicknesses we modeled the change in the irradiation efficiency with MCNP and found that this tolerance corresponds to a 0.5% uncertainty in the irradiation efficiency. The irradiation efficiencies (ε_{i}) that we calculate with MCNP are 0.509 and 0.521 for the NAD18A and NAD18E LOSs, respectively. Given the excellent narrow-beam geometry and well-characterized and simple shapes of the scattering materials, we estimate that the uncertainties on our calculated irradiation efficiencies are ±4%.

To determine the counting efficiency for the 5-cm diameter by 0.1 cm thick samples, we first measured the efficiency for counting a NIST traceable positron source and then scaled this result to the extended copper source geometry by modeling both geometries with MCNP. Since the range of the 2.9 MeV end-point energy positrons from the decay of ^{62}Cu is 1 mm, a significant fraction of the positrons would escape our 1 mm thick sample and annihilate in the NaI detectors themselves which needlessly complicates the counting geometry. To eliminate this effect we count the activated 1 mm thick copper samples between two, 2-mm thick copper disks to insure "local" annihilation of the positrons. To more closely emulate this NIF counting geometry in our calibration measurements, we obtained a thin ^{68}Ge source (initially 740 Bq ±3.1%) that could be sandwiched between copper disks of appropriate dimensions and located on axis. Like ^{62}Cu, ^{68}Ge is a nearly pure positron emitter.

The measured efficiency for counting the ^{68}Ge source in our NIF geometry was 0.144 ± 0.004. We next used MCNP to scale this efficiency to the geometry of a uniformly activated copper sample sandwiched between two, 2 mm copper disks, which predicted that the measured ^{68}Ge source counting efficiency must be reduced by a factor of 0.95. Thus, we estimate our counting efficiency (ε_d) to be 0.137 ± 0.008. This uncertainty includes the 3.1% source uncertainty and assumes a conservative uncertainty of 5% for the geometric correction factor of 0.95 obtained using MCNP. Combining all the uncertainties of the parameters in Eq. (2) gives a total systematic uncertainty of 7.3%.

The copper activation diagnostic has been successfully fielded on most DT experiments at NIF beginning with the first DT experiment. Results for many of the early experiments are presented in Leeper *et al.*[7] On cryogenic layered capsule shots, there can be significant areal density, (ρR), of cold fuel which can scatter the 14-MeV neutrons below the thresholds of the activation diagnostics and not contribute to the induced activity. If the implosion were symmetric the down-scattered ratio would be the same in all directions and the measured yield would be independent of angle. If the ρR were asymmetric, the presumed "isotropic" as measured yield will vary with angle and would be an indicator of ρR anisotropy.[10]

Any anisotropy can be measured by taking the ratio of NAD18A and NAD18E induced activities. Since both samples are counted on the same system, taking the ratio eliminates most of the systematic uncertainties and the result will be dominated by counting statistics, thereby increasing the sensitivity of the anisotropy measurement. Variations in this ratio are only affected by the sample masses, the distances from TCC, and the irradiation efficiencies and can be used to predict the ratio of activities assuming that the source is isotropic. If we then calculate a double ratio: the ratio of measured activities to the ratio of predicted, isotropic activities, we obtain a parameter $R_{\rho R}$, whose difference from "1" is a measure of anisotropy. $R_{\rho R}$ is given by

$$R_{\rho R} = \left[\frac{A_o^E}{A_o^A}\right]_M \left[\frac{A_o^A}{A_o^E}\right]_P = \left[\frac{A_o^E}{A_o^A}\right]_M \frac{m^A \varepsilon_i^A (d^E)^2}{m^E \varepsilon_i^E (d^A)^2}, \qquad (3)$$

where A_o is the initial activity, m is the sample mass, and d is the source to sample distance. "A" and "E" refer to the alcove and equator samples, respectively. "P" and "M" are for predicted and measured quantities, respectively. The masses and distances are known to <0.05%. The ratio of equator to alcove irradiation efficiencies was measured on two, assumed isotropic, exploding pusher shots to be 1.017 ± 5.4% which compares well with the MCNP calculated ratio of 1.023. Ratios with two-sigma error bars for four NIF cryogenic layered shots are shown in Fig. 2. The results are suggestive of ρR anisotropies but not conclusive.

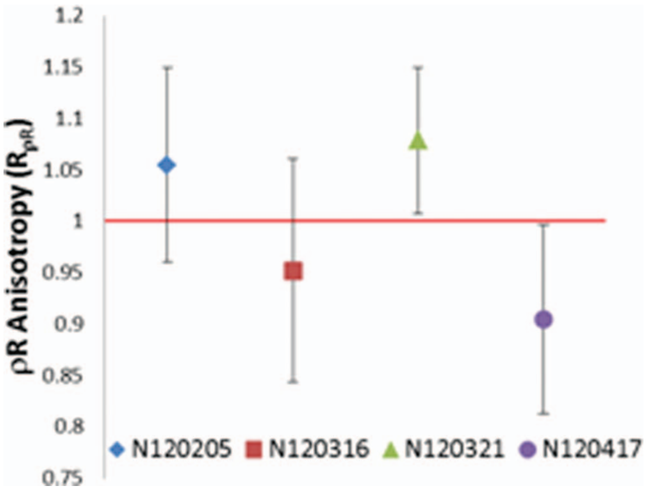

FIG. 2. Ratio of the measured, induced activities in NAD18E to NAD18A to the predicted ratio for four NIF cryogenic layered capsule shots. A ratio $R_{\rho R}$ = 1 represents perfect isotropy. The error bars are two-sigma.

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