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Measuring neutron yield and ρR anisotropies with activation foils at the National Ignition Facility

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Abstract. Neutron yields at the National Ignition Facility (NIF) are measured with a suite of diagnostics, including activation of ∼20–200 g samples of materials undergoing a variety of energy-dependent neutron reactions. Indium samples were mounted on the end of a Diagnostic Instrument Manipulator (DIM), 25-50 cm from the implosion, to measure 2.45 MeV D-D fusion neutron yield. The 336.2 keV gamma rays from the 4.5 hour isomer of ^{115m}In produced by (n,n′) reactions are counted in high-purity germanium detectors. For capsules producing D-T fusion reactions, zirconium and copper are activated via (n,2n) reactions at various locations around the target chamber and bay, measuring the 14 MeV neutron yield to accuracies on order of 7%. By mounting zirconium samples on ports at nine locations around the NIF chamber, anisotropies in the primary neutron emission due to fuel areal density asymmetries can be measured to a relative precision of 3%.

1. INTRODUCTION

Activation foils have long been used to measure neutron fluence and spectra for a variety of neutron sources. A chosen sample of material undergoes nuclear reactions upon exposure to neutrons above a certain energy threshold, creating a radioactive species. The subsequent decay of the radioactive nuclei can be measured and the number of neutrons passing through the material can be deduced. For an isotropic, instantaneous neutron source, the neutron yield, Y_n, above a reaction's energy threshold is calculated as

$$Y_n = \frac{4\pi R^2 A N_c}{m f_{BR} f_a N_A \epsilon_i \epsilon_d \langle\sigma\rangle e^{-\lambda(\Delta t_s)}[1 - e^{-\lambda(\Delta t_c)}]} \qquad (1)$$

where R is the distance from the neutron source to the activation sample, A is the atomic mass of the isotope undergoing the reaction of interest, N_c is the number of decay particles or gamma rays measured in a detector, m is the mass of the sample, f_{BR} is the branching ratio producing the detected radiation, f_a is the abundance of the isotope in the sample (including sample purity), N_A is Avogadro's number, ϵ_i is the irradiation efficiency (a deviation from unity indicating neutron absorption or scattering from environmental materials and in the sample itself), ϵ_d is the detection efficiency, $\langle\sigma\rangle$ is the spectrum-weighted cross section, λ is the decay constant of the radioactive material, Δt_s is the time between

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the irradiation and start of measurement and Δt_c is the time over which radiation from the sample is measured.

At the National Ignition Facility (NIF), to measure both neutron yield and implosion areal density variations, $\rho R(\Omega)$, neutron activation diagnostics (NADs) are implemented with five different methods, named for their deployment locations: Well-NAD, NAD20, DIM-NAD, Snout-NAD, and Flange-NAD. Indium is used to measure 2.45 MeV neutrons produced from deuterium-deuterium (D-D) fusion reactions while both zirconium and copper are used to measure 14 MeV neutrons from deuterium-tritium (D-T) reactions. As the thickness of these samples is generally 1 mm or greater, the nomenclature of "foil" is more historical than descriptive.

Presented here is a summary of the different activation foil implementation methods at NIF and representative results. The full analysis details and results for the past several years of NIF shots will be covered in a forthcoming publication [1].

2. WELL-NAD

Three zirconium foils of 1 mm, 3.5 mm, and 8.7 mm respective thicknesses are deployed in a diagnostic "well," on the NIF chamber at the (θ, ϕ) coordinates of (64,241), where $\theta = 0^\circ$ is the top of the chamber. The well allows insertion of the zirconium to 4.48 m from the capsule implosion, in front of the inside first wall of the chamber to minimize small-angle neutron scatter into the foils, but outside the chamber vacuum for easy retrieval. Neutrons from D-T fusion undergo ^{90}Zr(n,2n)^{89}Zr reactions in each sample while lower energy neutrons below the 12.1 MeV threshold do not react. A small $<2\%$ contribution to activation, currently included only in the uncertainty, is predicted from fuel-scattered neutrons above this threshold. The ^{89}Zr product then $\beta+$ decays with a 3.27 day half life to ^{88m}Y, which emits a 909 keV gamma ray several seconds later. These gamma rays are measured using lead-shielded high-purity germanium detectors in a low-background counting facility. A 5.7% overall reduction in sample activation due to absorption in the 1 cm thick wall of the well and scatter in surrounding materials (ϵ_i in Equation 1) was estimated with a Monte Carlo simulation using MCNP6 [2] and accounted for. The ^{90}Zr(n,2n) cross section is very well known, to less than 1% uncertainty around 14 MeV [3]. Assuming a Gaussian neutron spectrum centered at 14.07 MeV with a full width at half-maximum of 350 keV, the spectrum-weighted cross section, $\langle\sigma\rangle$, is 608 mb, including contributions from ^{90}Zr(n,2n)^{89m}Zr reactions decaying to the ^{89}Zr ground state with a 4.161 minute half life. This differs only slightly from the value of 607 mb for monoenergetic neutrons at 14.07 MeV, demonstrating an high insensitivity to the spectral width, broadened by the capsule fuel ion temperature. Uncertainties in each parameter of Equation 1 contribute to an overall yield uncertainty of about 7% and are tabulated elsewhere in these proceedings [4].

3. NAD20

The NAD20 diagnostic was named for its proximity to the "nToF20" neutron time-of-flight diagnostic, itself located about 20 m from the target chamber center in the "neutron alcove". Two copper foils, respectively 1 mm thick and 9.5 mm thick, are deployed both in front of the nToF20 detector array at 19 m from the implosion (NAD19) and behind (NAD29) the array at 29 m from the source in a well-shielded room. Neutrons from D-T fusion activate the copper samples via the ^{63}Cu(n, 2n)^{62}Cu reaction with an 11.0 MeV threshold, which subsequently decays by gammaless $\beta+$ emission. Because of the short 9.67 minute half life of ^{62}Cu, the samples must be retrieved and measured quickly. The 180°-opposed 511 keV gamma rays from annihilation of the emitted positron are detected in coincidence by two back-to-back NaI detectors, between which the sample is inserted within 30 minutes of irradiation. The competing ^{65}Cu(n, 2n)^{64}Cu reaction also decays by positron emission but with a 12.7 hour half life and its small contribution over short time scales is measured and subtracted. The yield uncertainty of the closest copper sample is typically $\sim$8%.

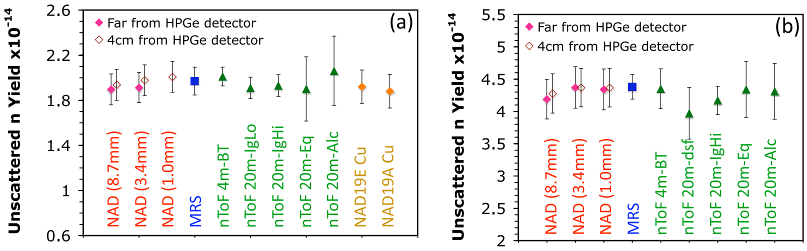

Figure 1. Primary unscattered neutron yield as measured from different diagnostics on two NIF shots: (a) N110217-001, an exploding pusher and (b) N110615-003, a layered DT shot. Well-NAD results (red, leftmost) are shown when the sample was counted both close to and far from the detector. NAD19 results (orange, right) are from copper foils on the equator (E) at (90,174) and in the alcove (A) at (116,315). The Magnetic Recoil Spectrometer (MRS) and neutron Time-of-Flight (nToF) diagnostics are described elsewhere in these proceedings.

Generally, yields determined by all three Well-NAD zirconium foils and both copper foils agree with each other and with the other yield diagnostics: the magnetic recoil spectrometer (MRS) and a variety of nToF detectors. An example is shown for two representative shots in Figure 1. The nToF detectors themselves are calibrated to a weighted average of these activation foils and the MRS on previous shots, however, and their agreement with these diagnostics is therefore demonstrative only of relative shot-to-shot consistency.

4. DIM-NAD AND SNOUT-NAD

Indium samples between 1–5 mm thick can be deployed two ways inside the NIF chamber to measure 2.45 MeV D-D neutrons. When mounted on the centerline of the end of a Diagnostic Instrument Manipulator (DIM), it is designated DIM-NAD. An indium holder was designed to attach to one of two other diagnostics, known as GXD and VISAR, depending on which of those diagnostics were last mounted on the DIM. When a DIM is otherwise in use, indium may be attached on the side of a DIM in a “Snout” normally used for the Wedge Range Filter (WRF) diagnostic, either behind the WRF components or alone.

The ^{115}In(n,n′)^{115m}In cross section rises rapidly between 1–2 MeV and remains relatively constant across the region around 2.45 MeV, making it relatively insensitive to ion temperature or scattered neutrons below ∼1 MeV. The ^{115m}In isomer emits 336.2 keV gamma rays with a 4.486 hour half life. These gamma rays are measured in the same low-background counting facility described in Section 2. Due to low neutron yields and a higher scattered-neutron sensitivity, indium activation must occur very close to the implosion with little shielding. The yield uncertainty when placed 50 cm from the target, enumerated similarly to that of zirconium, is typically ∼10%.

5. FLANGE-NAD

In a cryogenic layered capsule shot, there is a significant areal density (ρR) of cold fuel compressed throughout the fusion burn time. A significant percentage of primary 14 MeV neutrons scatter in this dense layer and lose enough energy to fall below the zirconium or copper cross section energy thresholds. Thus, it is understood that the absolute yield measurements are actually only measurements of the unscattered primary neutrons. Other diagnostics, such as the nToF detectors and the MRS, provide spectral information and attempt to measure these scattered neutrons in ratio to the unscattered yield to infer the ρR along a specific line-of-sight. In a perfectly symmetric capsule compression, this downscattered ratio and the yield would not change as a function of angle. However, anisotropies in the ρR will differentially reduce the primary unscattered yield along different lines-of-sight as neutrons

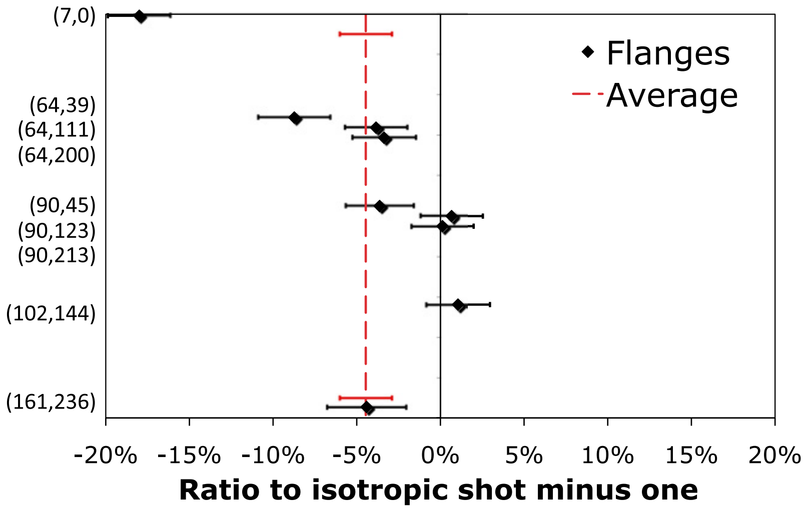

Figure 2. Flange-NAD results (see text) from the N110620-002 layered-cryogenic DT shot, relative to the assumed-isotropic N101030-002 exploding pusher shot. The ordinate is $\cos(\theta)$ with offsets to separate the three datapoints at $\theta = 64^\circ$ and 90°. The uncertainty in the average is the statistical uncertainty in the reference foil (well) activities.

pass through variant-ρR zones. The scattered yield, on the other hand, will increase along specific energy-dependent angles to their original path. To measure anisotropies in the yield, and therefore the capsule ρR, thick zirconium foils are placed on the outside of nine flanges at selected points around the chamber, at (θ, ϕ) coordinates: (7,0); (64,39); (64,111); (64,200); (90,45); (90,123); (90,213); (102,144); and (161,236). All foils are measured in the same detector in the same geometry to eliminate relative systematic uncertainties. By normalizing the activity from each flange position to that from the same flange measured in an assumed-isotropic exploding pusher shot and observing flange-to-flange differences in ratio to the reference zirconium sample from the Well-NAD measurement (also measured in the same detector and geometry), all uncertainties except for counting statistics are minimized down to as low as 3%. This double ratio of angular-dependent yields, $Y(\Omega)$, is derived from Equation 1 as

$$\frac{Y_A(\Omega_1)/Y_A(\Omega_2)}{Y_B(\Omega_1)/Y_B(\Omega_2)} = \left(\frac{m_{A2}m_{B2}}{m_{A1}m_{B1}}\right)\left(\frac{A^0_{A1}}{A^0_{B1}}\right)\left(\frac{A^0_{A2}}{A^0_{B2}}\right) \quad (2)$$

where the A and B subscripts designate, respectively, the layered cryogenic shot of interest and the isotropic exploding pusher; the 1 and 2 subscripts designate, respectively, the flange of interest and the reference sample (from Well-NAD); m is the mass of each sample and A^0 is the activity of each sample at the time of irradiation. The uncertainties in the masses are extremely small compared to that from the counting statistics. The residual of this quantity from unity is plotted for one particular NIF shot in Figure 2.

This particular result showed a high depression of unscattered yield from the top of the capsule, with the lowest apparent ρR along the equator. The repeating pattern amongst the three $\sim 90^\circ$-opposed foils on the 64° axis and those on the 90° axis, while small compared to uncertainties, suggests an azimuthal variation in ρR as well.

6. SUMMARY

Utilization of a suite of activation diagnostics has provided high-accuracy, independent measurements of yield along multiple lines-of-sight for relatively minimal cost and effort. Excellent agreement among multiple diagnostics lends high confidence to yield measurements. Significant anisotropies in ρR on some shots are being observed by activation foils in multiple locations around the NIF chamber.

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