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Absolute measurement of the DT primary neutron yield on the National Ignition Facility

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Abstract. The measurement of the absolute neutron yield produced in inertial confinement fusion target experiments conducted on the National Ignition Facility (NIF) is essential in benchmarking progress towards the goal of achieving ignition on this facility. This paper describes three independent diagnostic techniques that have been developed to make accurate and precise DT neutron yield measurements on the NIF.

1. INTRODUCTION

Three diagnostic systems have been developed to perform measurements of the absolute DT primary neutron yield on the NIF. An accurate and precise measurement of neutron yield to $\sim 5\%$ is essential to gauge progress towards ignition on NIF but several factors, especially neutron scattering cause errors. The first diagnostic is the magnetic recoil spectrometer that magnetically analyzes deuterium ions generated from neutron elastic scattering in a thin CD foil. The second system is a copper activation system that employs two different Cu samples. The third system is a zirconium activation system that employs three different Zr samples. The philosophy used in developing these three yield diagnostics is to use physical processes that are independent of each other to minimize systematic errors inherent in each technique. The focus of the paper will be on identifying and estimating these systematic errors as well as addressing statistical errors as a function of total neutron yield for each of these diagnostics. Finally, the paper will discuss a standard weighted least-squares procedure of combining the measured yields and associated errors of each technique into a final yield and best-estimated error. This procedure is an adaptation of the procedure used in particle physics to combine measurements and associated errors from a number of different experiments into a best-estimated value and corresponding error.

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Table 1. Systematic uncertainties for the MRS diagnostic are shown here.

MRS Parameter	Absolute	High-Res (%)	Med-Res (%)	Low-Res (%)
Foil area uncertainty	$\pm 0.2\,cm^2$	±1.5	±1.5	±1.5
Foil distance uncertainty	±0.3 cm	±1.1	±1.1	±1.1
Number density uncertainty	$\pm 10^{21}\,cm^3$	±1.3	±1.3	±1.3
Foil thickness uncertainty	$\pm 2.0\mu m$	±2.0	±0.8	±0.4
ND-cross section uncertainty	±12 mb/sr	±2.3	±2.3	±2.3
Magnet aperture area uncertainty	$\pm 0.2\,cm^2$	±1.0	±1.0	±1.0
Magnet aperture distance uncertainty	±0.1 cm	±0.02	±0.02	±0.02
Total systematic uncertainty for yield		±4.4	±4.0	±3.9

2. NIF ABSOLUTE NEUTRON MEASUREMENTS

One approach developed to measure the absolute DT primary yield on NIF is to use the NIF Magnetic Recoil Spectrometer (MRS). A detailed description of this diagnostic is given in Ref. [1–3]. Briefly the MRS has three main components. The first component is a CD foil positioned 26 cm from the implosion for production of recoil deuterons from incident neutrons; a focusing magnet located outside the NIF target chamber for energy dispersion and focusing of forward-scattered recoil deuterons onto the focal plane of the spectrometer; and an array of CR-39 nuclear track detectors, positioned at the focal plane, which records the position of each recoil particle with a detection efficiency of 100%. The spectrum of the recoil deuterons is determined by position at the detector plane, and used to determine the neutron spectrum. The yield reported from the MRS diagnostic is defined as the integral of the neutron spectrum between 13 MeV and 15 MeV and is referred to as the NIF primary neutron yield. The NIF MRS is designed to be operated in three resolution modes: (1) high resolution for DT neutron yields in the range of 10^{15}–10^{19}, (2) medium resolution for neutron yields in the range of 10^{14}–10^{18}, and low resolution for neutron yields less than 10^{14}. Table 1 shows the systematic uncertainties for the various MRS parameters and their contribution to the total systematic yield error for the MRS high-resolution, medium-resolution, and low-resolution modes. Typical MRS statistical errors are small. For example, the statistical error is less than 1% at a neutron yield at $\sim 2.5 \times 10^{14}$ when operated in the medium-resolution mode.

A second measurement of the NIF absolute DT total neutron yield is performed using a copper nuclear activation detector denoted Cu NAD. This technique employs the ^{63}Cu(n, 2n)^{62}Cu(β^+) reaction that has a total cross-section of 454.6 mb at 14.1 MeV [4–6]. The threshold energy for this reaction is 11.0 MeV that leads to yields inferred from Cu NAD that are higher by 2% to 5% relative to MRS yields depending on the neutron spectrum. The β^+ annihilation 0.511 MeV gamma rays are counted in NaI scintillator coincidence counting system that employs two 15.24 cm diameter by 7.62 cm NaI detectors. The half-life of ^{62}Cu is 9.67 minutes. A thin copper sample (Cu NAD19) that is 5.08 cm diameter by 0.1 cm thick is fielded at a position 19.0 m from target chamber center. A second thick copper sample (Cu NAD29) that is 7.62 cm diameter by 0.95 cm thick that is fielded at a distance of 29 m from target chamber center. Because the ^{62}Cu β^+ decay has an endpoint energy of 2.9 MeV, the thin copper sample is counted sandwiched between two copper disks that are each 5.08 cm diameter by 0.2 cm thick to insure that the β^+ stop and annihilate in a well defined region located between the two NaI scintillation detectors. The total systematic and typical statistical errors for the Cu NAD19 detector are shown in Table 2. Cu NAD29 views the neutron source through a rather complex neutron time-of-flight system located at 22 m. Because of the difficulty of accurately determining the neutron attenuation factor through this detector system, the Cu NAD29 detector is normalized to the Cu NAD19 detector using data obtain on several NIF neutron calibration shots.

Table 2. Systematic and typical statistical errors for the NIF Cu NAD19 detector are shown here.

Quantity	Value	Relative Error	Relative Error (%)
^{63}Cu Natural Abundance	0.6917	±0.0003	±0.04
^{62}Cu Decay Branching Ratio	0.9743	±0.0002	±0.02
Detector Counting Efficiency	0.1445	±0.00448	±3.1
Self Attenuation for 511 keV γ's	0.95	±0.0475	±5.0
Cross Section at 14.1 MeV (cm^2)	4.5459E-25	±5.8642E-27	±1.3
^{62}Cu Decay Half-life (min)	9.673	±0.008	±0.08
^{62}Cu Mean Half-life (min)	13.955	±0.011	±0.08
Sample Distance (cm)	1900.5	±1.9005	±0.1
Attenuation Factor	1.965	±0.0786	±4.0
Total Systematic Error			±7.3
Statistical Error (Yield $> 10^{14}$)			±1.0–2.0

Table 3. Systematic and typical statistical errors for the NIF Zr NAD diagnostic are shown here.

Quantity	Effect on Activity	Systematic Error (%)
Detector efficiency		±2.0–5.0
Gamma-ray self-shielding	−15%	Included in detector efficiency
Neutron "depletion" in zirconium		±0.6
Self-shielding differential from neutron depletion	−3.1%	±2.0
Cross-section uncertainty		±1.0
Position uncertainty		±1.1
Scatter/absorption off Al shield/well	−5.7%	±1.1
Chamber/wall scatter		$\pm <1$
Scatter off nearby materials		$\pm <1$
Down-scattered/non-primary neutrons		±2.0
Drift velocity/temperature peak shift (<100 keV)		±2.0
Ion temperature peak broadening		$\pm <1$
Sample purity (98.7%)	−1.35%	±0.2
Sample weight/oxidation/contamination		$\pm <1$
Total systematic error		±6.0
Statistical error (Yield $> 10^{14}$)		±1.0

A third measurement of the NIF absolute DT total neutron yield is performed using three samples of zirconium. A detailed paper on this technique is included in these proceedings [7]. Briefly, this technique uses the ^{90}Zr(n,2n)^{89}Zr reaction that has a total cross-section of 622.0 mb at 14.1 MeV. The threshold energy for this reaction is 12.1 MeV which leads to yields from Zr activation that are typically higher by at most 1% relative to MRS yields. ^{89}Zr decays to ^{89m}Y meta-stable state. ^{89m}Y has a half-life of 15.663 seconds and is in equilibrium with ^{89}Zr. The branching ratio of the internal transition 909 keV gamma ray is 99.2% and the half-life of ^{89}Zr is 3.267 days. An array of high purity Ge detectors is used to count the 909 keV lines emitted by the samples. The total systematic and typical statistical errors for this detector are shown in Table 3.

Table 4. Comparison of yield values obtained via Cu NADs, Zr NADs, and MRS along with the NIF authorized value for a representative number of NIF shots.

NIF Shot Number	Thin Cu Yield	Thick Cu Yield	Zr Yield	MRS Yield	Authorized NIF Value*
N110121 Layered THD	2.21×10^{13} $\pm 9.6\%$	2.01×10^{13} $\pm 10.0\%$	2.08×10^{13} $\pm 7.2\%$	2.10×10^{13} $\pm 5.0\%$	2.10×10^{13} $\pm 2.3\%$
N110212 Layered THD	1.27×10^{14} $\pm 7.9\%$	1.23×10^{14} $\pm 7.7\%$	1.18×10^{14} $\pm 7.7\%$	1.23×10^{14} $\pm 4.5\%$	1.25×10^{14} $\pm 2.3\%$
N110217 Exploding Pusher	1.88×10^{14} $\pm 7.9\%$	1.95×10^{14} $\pm 7.7\%$	1.94×10^{14} $\pm 7.1\%$	1.98×10^{14} $\pm 5.0\%$	1.94×10^{14} $\pm 1.5\%$
N110603-2 Exploding Pusher	2.18×10^{14} $\pm 7.5\%$	2.09×10^{14} $\pm 7.5\%$	2.14×10^{14} $\pm 7.4\%$	2.21×10^{14} $\pm 4.4\%$	2.17×10^{14} $\pm 1.8\%$

*Authorized values for layered shots include neutron time-of-flight detectors that were normalized to Zr activation.

3. NIF NEUTRON YIELD EXPERIMENTAL RESULTS

Table 4 shows a comparison of absolute DT yield values obtained from the Cu NAD19 (Thin Cu), Cu NAD29 (Thick Cu), Zr NAD and MRS diagnostics for a representative number of NIF shots. The authorized NIF values and associated errors shown in the table are determined from all four diagnostic measurements using a standard weighted least-squares technique. This procedure is an adaptation of the procedure used in particle physics to combine measurements and associated errors from a number of different experiments into a best-estimated value and corresponding error [8]. Examination of this table shows that the absolute neutron yields determined from all four measurements are in excellent agreement to within their errors giving confidence in this set of four absolute neutron yields. Applying the weighted least square-technique to this data enables a best-estimated NIF authorized value for the absolute neutron yield and its error for each NIF shot as shown in the table.

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