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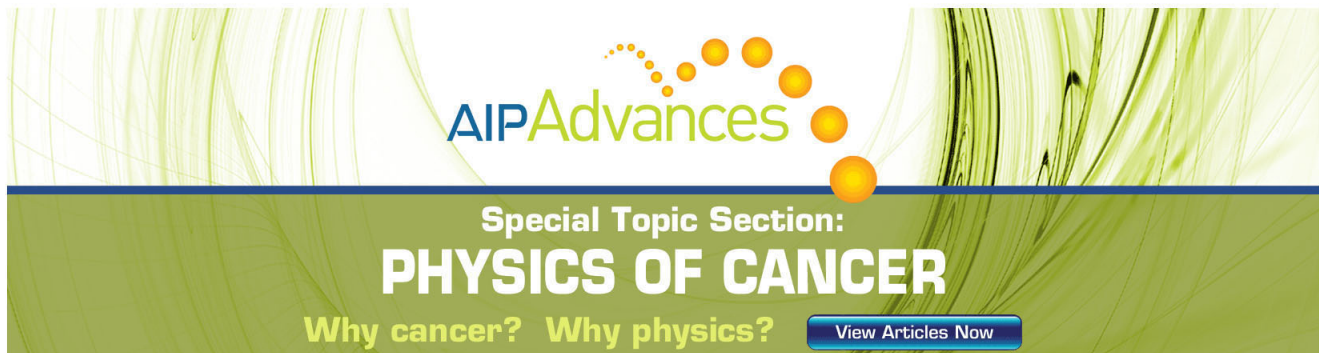
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Measuring the absolute deuterium–tritium neutron yield using the magnetic recoil spectrometer at OMEGA and the NIF^{a)}

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A magnetic recoil spectrometer (MRS) has been installed and extensively used on OMEGA and the National Ignition Facility (NIF) for measurements of the absolute neutron spectrum from inertial confinement fusion implosions. From the neutron spectrum measured with the MRS, many critical implosion parameters are determined including the primary DT neutron yield, the ion temperature, and the down-scattered neutron yield. As the MRS detection efficiency is determined from first principles, the absolute DT neutron yield is obtained without cross-calibration to other techniques. The MRS primary DT neutron measurements at OMEGA and the NIF are shown to be in excellent agreement with previously established yield diagnostics on OMEGA, and with the newly commissioned nuclear activation diagnostics on the NIF. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4738657>]

I. INTRODUCTION

In inertial confinement fusion (ICF) experiments performed at the OMEGA laser¹ and the National Ignition Facility (NIF),² the primary neutron yield is one of the most fundamental parameters that can be measured, as it relates to the number of fusion reactions and fusion energy released. Therefore, the yield will indicate if ignition^{3–5} has occurred in experiments currently being conducted at the NIF. Many yield diagnostic techniques^{6–9} exist, but the harsh ICF environment makes determining the absolute yield, with high accuracy, very challenging. Hence, multiple measurements conducted with different techniques are essential for establishing the fidelity of the resulting yield data. In particular, the yield from the magnetic recoil spectrometer (MRS) data is determined from first principles,^{10–13} without cross-calibration. In this paper, absolute yields obtained with the MRS are com-

pared to other techniques and the results indicate good agreement between the different measurements.

This paper is structured as follows: Section II discusses the diagnostic principle of the MRS. Section III shows the MRS yields at OMEGA and the NIF, and how these compare to other measurements. Section IV outlines future work, while Sec. V summarizes the paper.

II. THE MAGNETIC RECOIL SPECTROMETER (MRS) PRINCIPLE

The MRS consists of four main components; a CH₂ (or CD₂) foil positioned at 10 cm and 26 cm from the implosion at OMEGA¹ and the NIF,² respectively; a focusing magnet that is located outside the target chamber; and an array of CR-39 nuclear-track detectors positioned at the focal plane of the spectrometer. In addition to these four components, which are shown schematically in Figure 1, the MRS is enclosed by polyethylene shielding to suppress the ambient neutron background.

The MRS principle is as follows: a small fraction of the neutrons emitted from the implosion hit the CH₂ or CD₂ foil, producing forward-scattered recoil protons or deuterons. Some of these forward scattered recoil protons or deuterons are selected by an aperture, positioned in front of the magnet.

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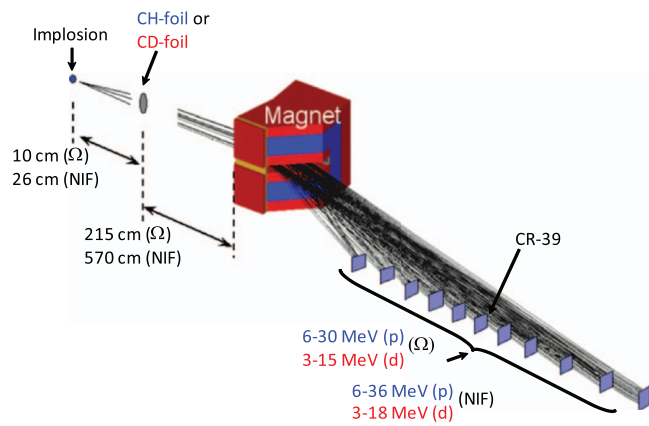


FIG. 1. A schematic drawing of the MRS and its three main components: a CH₂ (or CD₂) foil, magnet, and an array of CR-39 detectors. The MRS uses the foil to convert incident neutrons into recoil charged particles. Forward scattered recoil protons or deuterons are selected by an aperture in front of the magnet. Selected recoil particles are momentum analyzed and focused onto an array of CR-39 detectors, which record the position and therefore energy of each recoil particle. The measured recoil spectrum is then used to determine the neutron spectrum from the implosion. The polyethylene neutron shielding that encloses the MRS is not shown.

The selected recoil particles are energy-dispersed by their momentum in the MRS magnetic field and focused onto an array of CR-39 detectors. The measured recoil spectrum is then used to determine the neutron spectrum emitted from the implosion.

III. MRS MEASUREMENTS OF THE YIELD ON OMEGA AND THE NIF

The DT reaction yield (Y_{DT}) is determined from the number of counts (S) in the MRS measured spectrum (in the region corresponding to the Doppler broadened primary neutron spectrum) (Ref. 14) and detection efficiency of the system (ϵ_{DT}), which is a function of the foil and system parameters (discussed in detail in Ref. 15). If capsule self-attenuation is small and there are no other significant sources of neutrons in the vicinity of the primary spectrum, such as down-scattered neutrons (DSn) produced in high areal density ($>0.1 \text{ g/cm}^2$) implosions, then the reaction yield can be determined directly using $Y_{DT} = S/\epsilon_{DT}$. As the detection efficiency is a function of neutron energy (caused by the energy dependence of the elastic (n,d) scattering cross-section in the foil),¹⁶ a primary-neutron weighted ϵ_{DT} must be used in the analysis. In high- ρR implosions at the NIF, attenuation and the resulting DSn spectrum near the DT peak are significant and must be considered. An estimate of the difference between Y_{DT} and the observed neutron yield due only to attenuation can be derived by calculating the approximate number of DT neutrons that scatter. This is $\sim 1 - e^{-\rho R \sigma/m}$, or simply $\sim 0.2 \rho R [\text{g/cm}^2]$ for $\rho R < 1 \text{ g/cm}^2$. Thus, the actual reaction yield is higher than the observed yield by $\sim 2\%$ for a 0.1 g/cm^2 implosion. Therefore, a standard integral over the energy range of 13–15 MeV is used for the determination of the neutron yield (or Y_{13-15}) that includes some amount of attenuation and DSn. The energy dependence of ϵ_{DT} is accounted for through a forward-fit analysis of the measured spectrum using the MRS

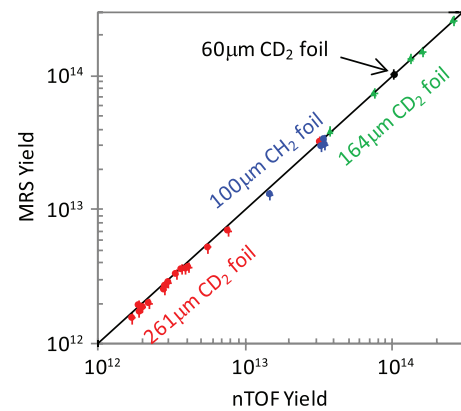


FIG. 2. OMEGA MRS primary neutron yield as a function of nTOF primary neutron yield. Excellent agreement between the measurements is observed for a wide range of implosion-yields. Three different CD₂ foils and one CH₂ foil were used for the MRS in these experiments.

response function. For high- ρR implosions, determining the relationship between the measured (and reported) Y_{13-15} and the actual DT reaction yield requires either measurement of the full neutron spectrum (with models of the various components) or coupled hydrodynamic and neutron transport modeling of attenuation and neutron scattering during the implosion, performed using codes such as LASNEX or HYDRA.⁵

At OMEGA, the MRS is complemented by neutron time-of-flight (nTOF) detectors.^{6,7,17} The systematic uncertainty of the nTOF yield data is 5% at OMEGA,^{18,9,19} while the systematic uncertainty associated with the OMEGA MRS and the NIF MRS yield is 9% and 4.3%, respectively. Figure 2 shows the determined MRS primary yields produced in gas-filled and cryogenic DT implosions, compared to nTOF primary yields, ranging from $Y_{DT} \sim 2 \times 10^{12}$ to 2×10^{14} . A 100 μm thick CH₂ foil and three different CD₂ foils (ranging from 60 to 261 μm in thickness) were used for these measurements. For each foil, ϵ_{DT} must be calculated based on the measured foil-specifications.¹⁵ Because much of the systematic uncertainties associated with the MRS yield are foil-specific, using multiple foils results in a smaller systematic error of 6% compared to 9% estimated for a single foil. The data show excellent agreement between the two measurements over several orders of magnitude. The MRS provides a yield that is on average 0.97 ± 0.01 (statistical error only) of the nTOF yield.

A large suite of nuclear diagnostics has been commissioned on the NIF. This includes the MRS, nTOFs,⁷ neutron imaging,²⁰ Zr (Refs. 19 and 21) and Cu (Refs. 6 and 8) nuclear activation diagnostics (NADs), and the Gamma-ray-burn-history (GRH) detector.²² These diagnostics have been fielded on DT gas-filled exploding-pusher implosions and cryogenically layered DT and THD implosions, producing a wide range of neutron yields. The MRS yield has been compared to the NADs measurements, averaged over several different lines-of-sight,²¹ which are also absolutely calibrated (the NIF nTOF detectors were calibrated with the MRS and NADs data and thus excluded in this comparison).²³ The yields determined from the MRS data, as a function of the activation data, are shown in Figure 3. Here, five different CD₂ foils were used with thickness ranging from 47 to 259 μm .

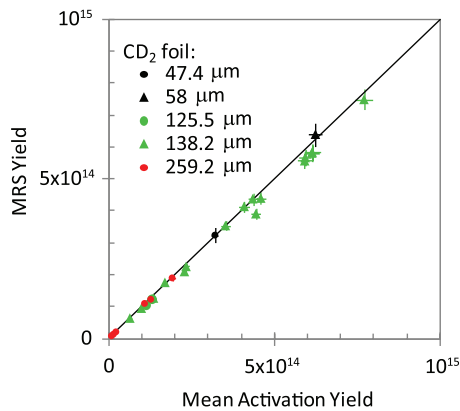


FIG. 3. Absolute primary neutron yield (integrated between 13 and 15 MeV) measured by the NIF MRS as a function of the primary yield measured by the nuclear activation diagnostics (uncertainty weighted mean). Given the absolute uncertainties, excellent agreement between the measurements is observed, providing confidence in the absolute primary yield measured at the NIF.

Again, each foil has a different ϵ_{DT} and the comparison using multiple foils decreases the MRS systematic error to 3.6%. Excellent agreement between the two sets of data is observed. On average, the MRS-to-activation-yield ratio is 0.98 ± 0.02 (for all DT shots from September 2010 to April 2012).

IV. FUTURE WORK

As the systematic uncertainties are typically larger than statistical uncertainties in the MRS data, better characterization of the different MRS parameters will reduce the uncertainty in the determined primary neutron yield. We are in the process of reducing the dominant sources of the systematic uncertainties. At both OMEGA and the NIF, the uncertainty in the differential cross-section for (n,d) elastic scattering in the foil is important. Faddeev calculations of the (n,d) elastic scattering cross-section, for neutron energies in the range 3–18 MeV, were recently conducted to an accuracy of 1%.^{24,25} These cross-sections are planned to replace the cross-sections currently used¹⁶ in the modeling of the MRS-response function, improving the systematic uncertainty in NIF-MRS yield from 4.3% to 3.7%. For the OMEGA MRS, the uncertainty due to geometric and positioning issues (8%) needs to be considered as well. A redesigned foil holder is expected to improve the systematic uncertainty from 9% to 6%.

V. SUMMARY

As the MRS detection efficiency is determined from first principles, the absolute primary neutron yield from an

ICF implosion is determined directly from the measured data without cross-calibration. The results obtained at OMEGA and the NIF are in good agreement with other measurements, clearly demonstrating the high fidelity of the yield data at these facilities. To enhance the capability of the MRS, the systematic uncertainties associated with the MRS yield measurement are actively being reduced.

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