γ-to-neutron branching ratio for deuterium-tritium fusion determined using high-energy-density plasmas and a fused silica Cherenkov detector

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A fused silica Cherenkov detector was used to measure deuterium-tritium (DT) gammas during a set of 52 direct-drive cryogenic experiments performed at OMEGA. The detector was calibrated using the 4.4 MeV γ from the first-excited state of carbon, which is produced when 14-MeV DT neutrons impinge upon a carbon puck. An approximate DT γ spectrum as well as neutron yields from a standard neutron time-of-flight detector at OMEGA were used to calculate a DT γ-to-neutron branching ratio of $(8.42 \pm 2.84) \times 10^{-5}$. Assuming an excited-state to ground-state ratio of 2.1 : 1, the measurement detailed in this work results in an approximate ground state only γ-to-neutron branching ratio of 2.72×10^{-5}. This value is somewhat lower than accelerator-based measurements of the ground-state DT γ only.

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I. INTRODUCTION

Inertial confinement fusion (ICF) experiments generally involve laser-driven implosion of spherical deuterium-tritium (DT) targets, increasing temperatures and pressures to levels at which fusion can occur. The goal of these experiments is generally to produce a self-sustaining burn through redeposition of energy by the α particles that are produced by the D(T, α)n reaction. Products of the fusion reactions such as x rays, neutrons, and charged particles can be detected and used to evaluate the physical conditions present in a given implosion as well as to assess overall performance of the implosion's design.

Study of the reaction history of a given implosion is vital to diagnosing thermonuclear burn. While the neutrons from the D(T, n)α reaction are often used for this purpose, these neutrons are known to scatter both on material within the target as well as on exterior structures surrounding the implosion. Gammas from the alternate branch D(T, γ) ^{5}He are arguably the better choice for diagnosing burn history because they exit the target without scattering and are not affected by Doppler broadening. Absolute γ reaction history for DT implosions requires a well-known DT γ-to-neutron branching ratio as well as good calibration of the detectors used to make the measurement.

The DT γ is additionally interesting within the context of nuclear physics due to its relationship to the ^{5}He nucleus. It is well known that the DT γ has a spectral shape that is associated with the ground state and the first-excited state of ^{5}He such that the two possible γ branches are

$$\mathrm{D} + \mathrm{T} \longrightarrow {}^5\,\mathrm{He} + \gamma_0 \tag{1}$$

and

$$\mathrm{D} + \mathrm{T} \longrightarrow {}^5\,\mathrm{He}^* + \gamma_1, \tag{2}$$

where γ_0 is associated with the ground state of ^{5}He while γ_1 is associated with the first-excited state of ^{5}He (^{5}He*). ^{5}He is particularly significant as one of the smallest nuclei that is thought to have a shell structure. Two neutrons and two protons are at the center of the shell while one neutron is contained within an outer shell. The mass and width of its ground state can be accurately calculated via the nuclear shell model, however, the nuclear shell model is not able to accurately predict the parameters of excited states.

As experimental measurements of the mass of the ground state of ^{5}He are in agreement with one another and with the prediction by the nuclear shell model, the energy of γ_0 is well known to be about 16.7 MeV. The first-excited state of ^{5}He is, however, poorly known, with experimental values in the existing literature spanning a wide range. Recent literature involving ICF-based measurements of the DT γ reports the ratio $\gamma_1 : \gamma_0$ to be about $(2.1 \pm 0.4) : 1$ [1].

To date, two studies have attempted to determine the DT γ-to-neutron branching ratio on an ICF platform using the gas Cherenkov detectors (GCD's) at OMEGA. The first ICF-based measurement was made using GCD-1 at OMEGA [2,3]. At the time, the calibration for GCD-1 was not very precise,

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resulting in a measured DT γ-to-neutron branching ratio of $(4.2 \pm 2) \times 10^{-5}$ [2], which has a 48% error bar. Nonetheless, this ICF-based measurement represented a significant improvement over previous accelerator-based results, which have inferred DT γ-to-neutron branching ratios spanning over an entire order of magnitude. It is thought that this is likely due to neutron-induced background on the γ measurements, as nuclei in solid accelerator targets can enter an excited state when impinged upon by 14-MeV DT neutrons and will then emit gammas as they return to their ground states. The configuration of ICF experiments minimizes this issue since warm DT targets typically consist of a relatively thin outer layer around a volume of gaseous DT. A more recent measurement using GCD-3 (a detector similar to GCD-1, but with some design improvements) used an absolute calibration based on the $C(n, n')\gamma$ cross section. This resulted in a branching ratio of $(4.56 \pm 0.58) \times 10^{-5}$ [4]. This measurement has a similar mean value to that reported in Refs. [2] and [3], but its uncertainty is smaller due to calibration to a relatively well-known cross section. Note, however, that these two measurements both used very similar instruments, so it is expected that they should obtain similar mean values so long as both used valid calibration procedures.

The present measurement uses a quartz-based Cherenkov detector with a calibration based on the $C(n, n')\gamma$ cross section to evaluate the DT γ-to-neutron branching ratio using data collected during cryogenic DT implosions at OMEGA.

II. DETECTOR AND CALIBRATION

The detector used for this measurement is known as the diagnostic for areal density (DAD). It uses Cherenkov radiation in quartz to detect gammas generated during direct-drive ICF experiments at OMEGA. This detector was originally built for the purpose of diagnosing remaining shell areal densities on warm implosions via measurement of 4.4-MeV gammas from the first-excited state of carbon [5] but is capable of measuring any gammas above ≈0.4 MeV. The DAD consists of 6 mm of tungsten shielding in front of a 6.39-cm diameter, 5-cm-thick piece of fused silica which is directly paired to a photomultiplier tube (PMT). This assembly is situated directly on the wall of the OMEGA target chamber. The face of the detector is located ≈172.3 cm from target chamber center (TCC) while the PMT and electronics are located outside the target chamber wall. For comparison, the GCD-1 detector used in Refs. [2] and [3] uses Cherenkov radiation in CO_2, which allows for detection of gammas above ≈6.3 MeV only. GCD-3, the updated version of GCD-1 which was used in Ref. [4], allows for the detection of gammas above ≈2.6 MeV when using CO_2 as its radiator.

It is important to note that all γ detectors that are currently available at ICF facilities are temporally resolved current-mode detectors, i.e., the measured signals are voltages as a function of time. These measured signals do not provide any direct spectral information. Due to the very short (≈100 ps) timescales associated with ICF experiments, time-integrated methods such as pulse-height γ detection cannot be used for this application. This means that detectors such as the DAD and GCD's cannot be calibrated using the standard procedures that are employed for pulse-height γ detectors. They can instead be calibrated using the relatively well-known (n, γ) cross section for 14-MeV DT neutrons on carbon [i.e., $C(n, n')\gamma$].

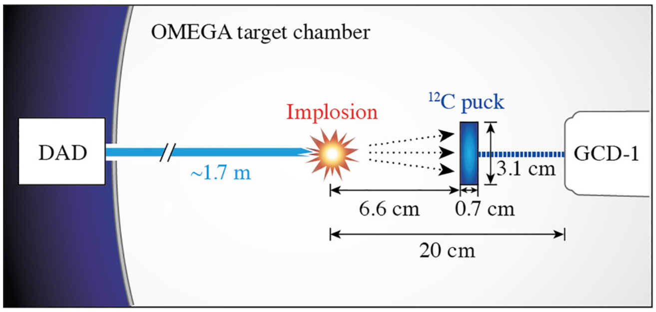

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FIG. 1. Diagram illustrating the set up for the DAD carbon calibration. GCD-1 is used to hold a carbon puck near TCC. DAD detects the backwards-directed gammas. Image originally published in Frontiers in Physics (see Ref. [8] for full citation).

This is generally accomplished at OMEGA using a carbon puck which is fielded inside the target chamber during a warm DT implosion [6,7]. The DT implosion produces 14-MeV neutrons. When these neutrons impinge upon the carbon puck, 4.4-MeV carbon gammas (from the first-excited state of carbon) are produced with some time delay relative to the prompt DT gammas. The DAD does not have an attachment for adding a carbon puck in front of the detector, so GCD-1 was used to hold a carbon puck near TCC for this measurement while the DAD detected carbon gammas from the other side of the target chamber, as shown in Fig. 1.

Background shots without the carbon puck present are also necessary in order to isolate the signal from the carbon gammas only. These background shots must include the puck-holder apparatus (without the carbon puck installed) to accurately isolate the carbon γ signal. The final carbon γ signal can then be obtained by subtracting the background data from the data collected with the carbon puck present. Figure 2 shows some representative signals that were collected for use in the DAD calibration. Once the carbon γ signal has been isolated, the calibration constant χ can be calculated as detailed in Ref. [7] such that

$$\chi = \frac{A}{Y_{DTn}\ \Omega\ R\ e\ QE\ G\ C_{ph}(4.4\ \text{MeV})} \frac{m_C}{f_1\ \sigma} \frac{4\pi D^2}{M_{\text{puck}}}, \qquad (3)$$

where A represents the area of the carbon γ signal, Y_{DTn} represents the DT neutron yield, Ω represents the detector solid angle, R represents digitizer impedance (i.e., 50 Ω), e represents electron charge, QE represents the PMT's quantum efficiency, G represents the PMT's gain, $C_{ph}(4.4\ \text{MeV})$ represents the detector response (i.e., Cherenkov photons produced per incident γ) to 4.4-MeV gammas as simulated by Monte Carlo, m_C represents the mass of one carbon atom, f_1 is a geometric efficiency factor which accounts for different scattering angles [6], σ represents the total cross section for the inelastic scattering of DT neutrons on carbon, D represents the carbon puck's distance from TCC, and M_{puck} represents

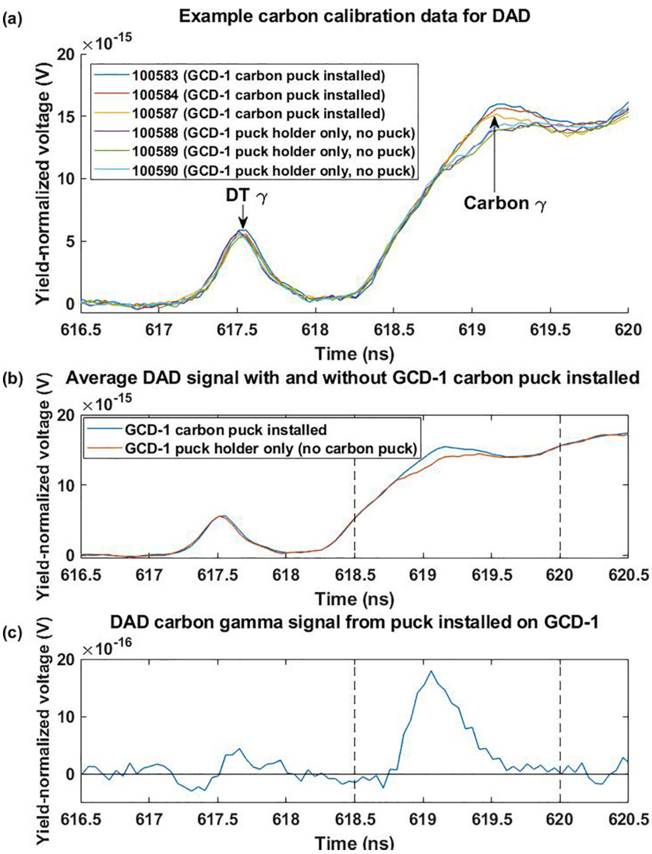

FIG. 2. Example of carbon calibration for the DAD. Some representative signals with and without the carbon puck are shown in panel (a). As shown in panel (b), multiple signals were averaged together to obtain an average signal with and without the carbon puck. The average signal without the puck was then subtracted from the average signal with the puck in order to isolate the signal from carbon gammas shown in panel (c). Image originally published in Frontiers in Physics (see Ref. [8] for full citation).

the mass of the carbon puck. Note that the geometric factor f_1 is a function of the carbon cross section at the relevant puck-to-detector angle and that the carbon cross section does vary with scattering angle, so this factor accounts for the fact that the DAD receives backwards-directed gammas from the carbon puck according to the setup shown in Fig. 1 (while GCD-1, for example, would receive forwards-directed gammas in this configuration). DT neutron yields were measured using a standard neutron time-of-flight (nTOF) detector at OMEGA [9].

The carbon calibration constant for the DAD was calculated using the carbon cross-section data detailed in Ref. [7] for a final result of $\chi = 3.10 \pm 0.47$. The uncertainty on the DAD calibration constant is comprised of 9% systematic uncertainty and 6% statistical uncertainty. Systematic uncertainties are from the DT neutron yield (5%), the mass of the puck (2%), and the total carbon cross section (2.5%). These quantities are added in quadrature to calculate the total systematic uncertainty. Statistical uncertainties are from the DT neutron yield (1.5%), the area calculation shown in Fig. 2 (7%), the angularly resolved carbon cross section (6%), and Cherenkov statistics (2%). These quantities are added in quadrature to calculate the total statistical uncertainty. The total uncertainty on the calibration is the sum of the systematic and statistical uncertainties. Although these two quantities could be propagated through the γ measurements in the following calculations separately, the choice was made to combine these uncertainties to maintain a quantity that is analogous to the GCD-3 calibration in Ref. [7], where only the total uncertainty is provided and used as a contributor of systematic uncertainty on subsequent measurements.

Once the calibration constant is known, it can be used to calculate γ yield based on a measured signal such that

$$Y_\gamma = \frac{A_\gamma}{\Omega\ R\ e\ QE\ G} \frac{1}{C_{ph}(E_\gamma)\chi}. \quad (4)$$

Note that the detector response $C_{ph}(E_\gamma)$ must be calculated at the relevant γ energy. As Cherenkov detectors utilized at ICF facilities are temporally resolved, current-mode detectors with some energy threshold and not true γ spectrometers, the relevant γ energy for a given implosion may often be assumed based on kinematic considerations. The case of the DT γ is, however, additionally complicated due to its spectrum, which is known to span a wide range of energies.

III. DEUTERIUM-TRITIUM γ-TO-NEUTRON BRANCHING-RATIO MEASUREMENT

The DAD branching ratio measurement was based on data collected during a series of 52 cryogenic DT experiments. Although data also exists for many glass-shelled, shock-driven (i.e., "exploding pusher") experiments such as those used to obtain carbon calibration data, it is known that the collision of DT neutrons with unablated shell material can cause emission of secondary gammas. This generally occurs because the kinetic energy imparted to the silicon and oxygen in the remaining shell cause these nuclei to enter excited states. Several gammas of various energies are emitted upon decay to their ground states. As oxygen has many excited states and the DAD was designed to be sensitive to low-energy gammas, gammas from a glass shell can constitute a significant contribution to the total γ signal observed by the DAD even if the glass shell's areal density is as low as only 1 mg/cm^2 [5,10]. In contrast, cryogenic experiments use an outer shell of CD which is completely ablated during direct-drive implosions such as those performed at OMEGA [5]. As shown in Fig. 3, plotting the DAD γ signal area vs DT neutron yield for both cryogenic and glass-shelled implosions shows that there is indeed $\approx 2.3\times$ more total γ signal per DT neutron in glass-shelled implosions.

The relevant cryogenic data set used for the DT branching-ratio measurement spans DT neutron yields of 9.5×10^{13} to 1.6×10^{14} and ion temperatures of 2.7 to 6.4 keV. The DT γ signal area was calculated for each of these shots. The DT γ signal generally has an approximately Gaussian shape and can be identified as the first distinguishable feature in the DAD signal, as illustrated in Fig. 2. For reference, these DT ion temperatures of 2.7 through 6.4 keV correspond to a range of center-of-mass (CM) energies from 14 to 26 keV. The average

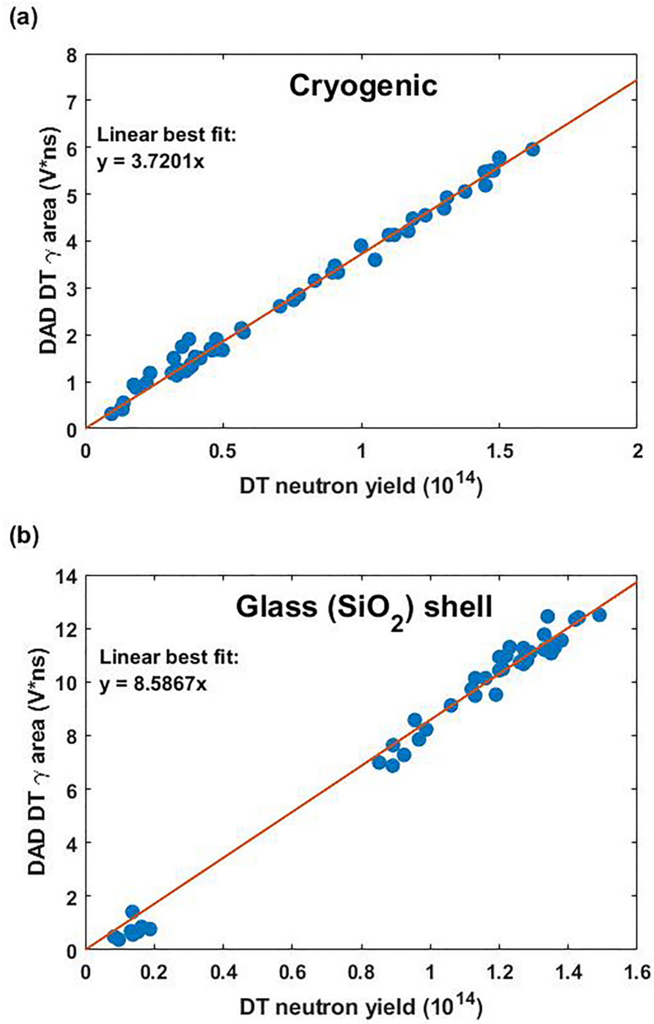

FIG. 3. DAD γ signal area vs DT neutron yield for (a) cryogenic and (b) glass-shelled implosions. There is a factor of $\approx 2.3\times$ more signal in glass implosions due to gammas that are produced when DT neutrons interact with silicon and oxygen in the remaining shell. The cryogenic data are used for the DT γ-to-neutron branching-ratio measurement because these data are representative of measured signal related to the DT fusion gammas only. The data from the glass-shelled implosions can, however, still be useful for background subtraction in other γ measurements that require subtraction of shell gammas.

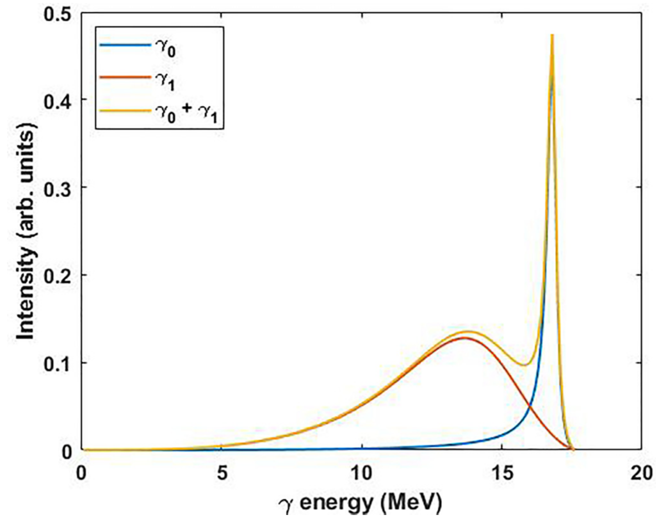

FIG. 4. DT γ spectrum from Ref. [1], which was used to determine the appropriate weighting for the detector response in the calculation of DT γ yield. The blue curve represents the γ associated with the ground state of ^{5}He while the red curve represents the γ associated with the first-excited state of ^{5}He. The yellow curve represents the sum of the two. Spectrum provided by coauthor Kim (Los Alamos National Laboratory). Image originally published in Frontiers in Physics (see Ref. [8] for full citation).

ion temperature for the data set was 4.5 ± 0.5 keV, which corresponds to an average CM energy of 19 ± 2 keV.

A linear fit to the DAD signal area vs DT neutron yield data was performed in order to determine an average relationship between the γ signal area and the DT neutron yield. This linear fit is shown in Fig. 3 and results in a best-fit function of $A_{DT\gamma} = 3.72 \times (Y_{DTn}/10^{14})$. The signal area appears to be independent of ion temperature (and therefore independent of CM energy) within this range of ion temperatures. The γ-to-neutron branching ratio for this data set is therefore also independent of ion temperature and CM energy.

This value for DT γ signal area divided by the DT neutron yield can be used in Eq. (4) to determine the number of DT gammas per neutron. One complication in using Eq. (4) for the DT γ is that it is known that the DT gammas are produced across a wide range of energies associated with the mass and width of the ^{5}He ground state and first-excited state. This affects the detector response that should be used in Eq. (4). The recent DT γ spectrum from Ref. [1] was used to determine the effective response for this measurement. Ref. [1] gives a nominal γ spectrum with an excited-state γ to ground-state γ ratio of $\gamma_1 : \gamma_0 = (2.1 \pm 0.4) : 1$. For reference, this spectrum is shown in Fig. 4. This spectrum can be used as a weighting on the DAD response function to determine the total response that is appropriate for this measurement. Use of the weighted response causes a 19% decrease in the calculated γ yield in comparison to the monoenergetic 16.7 MeV response for the DAD which would be used if it were assumed that the DT γ spectrum produced only monoenergetic ground-state gammas.

Systematic and statistical uncertainties were calculated separately. Systematic uncertainties on this measurement include contributions from relative gain (10%), relative QE (10%), DT neutron yield (5%), calibration (15%), and the weighted response (10%). The uncertainty on the weighted response reflects the uncertainty in the $\gamma_1 : \gamma_0$ branching ratio. Realistically, the shape of the nominal DT γ spectrum and the shape of the DAD response cause an asymmetric change in the weighted response when the $\gamma_1 : \gamma_0$ branching ratio varies. There is a 1.2% increase in the branching ratio due to the effective response when the $\gamma_1 : \gamma_0$ ratio is taken to be 2.5 instead of 2.1. In contrast, there is a 9.7% decrease due to the effective response when the $\gamma_1 : \gamma_0$ ratio is taken to be 1.7 instead of 2.1. The larger of the two was chosen in order to make a conservative estimate of the total systematic uncertainty.

The statistical uncertainty on this measurement comes from the variation on the signal area per DT neutron as well as from the statistical uncertainty on the DT neutron yield (1.5%) and additional statistical uncertainties from the distribution of Cherenkov photons. The variation on the signal area per DT neutron was determined by calculating the standard deviation on the data points shown in Fig. 3 such that

$$\sigma = \sqrt{\frac{\sum_i (A_i - \bar{A})^2}{N}},$$

where A_i is a γ signal area per DT neutron from an individual measurement, $\bar{A}$ is the average γ signal area per DT neutron (i.e., the slope of the linear fit), and $N = 52$ is the number of measurements. The calculated variation was approximately 10%.

The distribution of Cherenkov photons produced in the detector as well as the distribution of photons that reach the photocathode per electron (i.e., the "bunch size") were determined using GEANT4 simulations of the detector. As detailed in Ref. [7], the number N of detector events (i.e., the number of photon-producing electrons) can be calculated from the total number N_{Ch} of Cherenkov photons and the average bunch size μ_{Ch} such that

$$N = \frac{N_{\mathrm{Ch}}}{\mu_{\mathrm{Ch}}}. \tag{5}$$

The total statistical uncertainty on N can then be calculated such that

$$\sigma_N = N\sqrt{\frac{1}{N_{\mathrm{Ch}}} + \frac{V_{\mathrm{Ch}}}{\mu_{\mathrm{Ch}} N}} + \sqrt{N}, \tag{6}$$

where V_{Ch} is the variance on the bunch size. The first term in Eq. (6) therefore represents statistical uncertainty from the number of Cherenkov photons calculated in Eq. (5) while the second term represents statistical uncertainty in the number of incident gammas [7]. The results of the GEANT4 simulations are shown in Fig. 5. The final contribution from Cherenkov photons and detector events was approximately 1%.

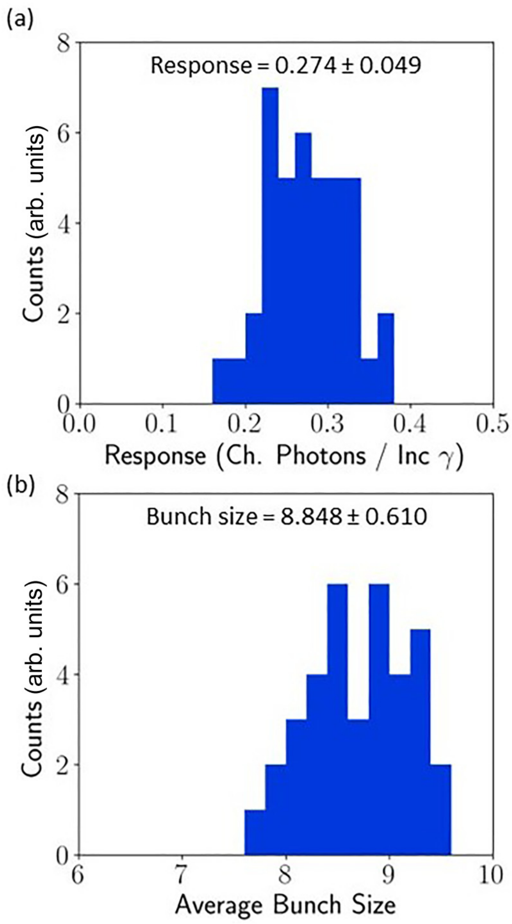

FIG. 5. Results of GEANT4 simulations for DT gammas incident on DAD. The spectrum used in Ref. [1] was used to sample the relevant γ energies. The number of gammas incident on DAD was calculated assuming a conservative yield of 10^{13} DT neutrons and using the branching ratio from Ref. [2] with the DAD solid angle. The statistical uncertainty calculated using the results of these simulations therefore represents a maximum statistical uncertainty, as the branching ratio assumed in these simulations is smaller than the branching ratio as determined in this work. Simulations were performed by coauthor Rubery (Lawrence Livermore National Laboratory)

Adding the systematic uncertainties in quadrature with each other, the final systematic uncertainty was 23%. Adding the statistical uncertainties in quadrature with each other, the final statistical uncertainty was 10%. The final DT γ-to-neutron branching-ratio measurement was $(8.42 \times 10^{-5}) \pm (0.86 \times 10^{-5})_{\mathrm{stat}} \pm (1.98 \times 10^{-5})_{\mathrm{sys}}$. This branching ratio is shown along with previous measurements of the DT γ-to-neutron branching ratio, including the GCD results from Refs. [2–4], in Fig. 6. The DAD branching ratio calculated in this work is about a factor of two higher than the GCD branching ratio reported in Refs. [2–4]. It is clear, however, that the error bars from this measurement overlap with those reported in Refs. [2] and [3], so these measurements can be said to agree with each other.

It should also be noted that the DAD measurement seems reasonable as a measurement of $\gamma_0 + \gamma_1$ in relation to accelerator measurements which claim to have isolated the γ_0 spectrum. The previous ICF-based measurements from Refs. [2–4] were lower than the γ_0-only accelerator measurements at similar CM energies, which is puzzling considering the fact that DT γ measurements conducted with current-mode detectors used at ICF facilities measure the sum of the γ_0 and γ_1 branches. Considering the $\gamma_1 : \gamma_0$ ratio of 2.1 : 1 reported in Ref. [1], the measurement reported here can be divided by 3.1 to get an approximate γ_0 only branching ratio of $\approx 2.72 \times 10^{-5}$. This number is somewhat lower than the accelerator data from Refs. [14] and [15], which give average ground-state γ-to-neutron branching ratios of $(5.4 \pm 1.3) \times 10^{-5}$ and $(5.6 \pm 0.6) \times 10^{-5}$, respectively. Nonetheless, this result appears to be more logically consistent with the accelerator data than the GCD-based measurements [2–4] due to the fact that the total $\gamma_0 + \gamma_1$ is larger than the γ_0 only accelerator data as well as the fact that accelerator experiments

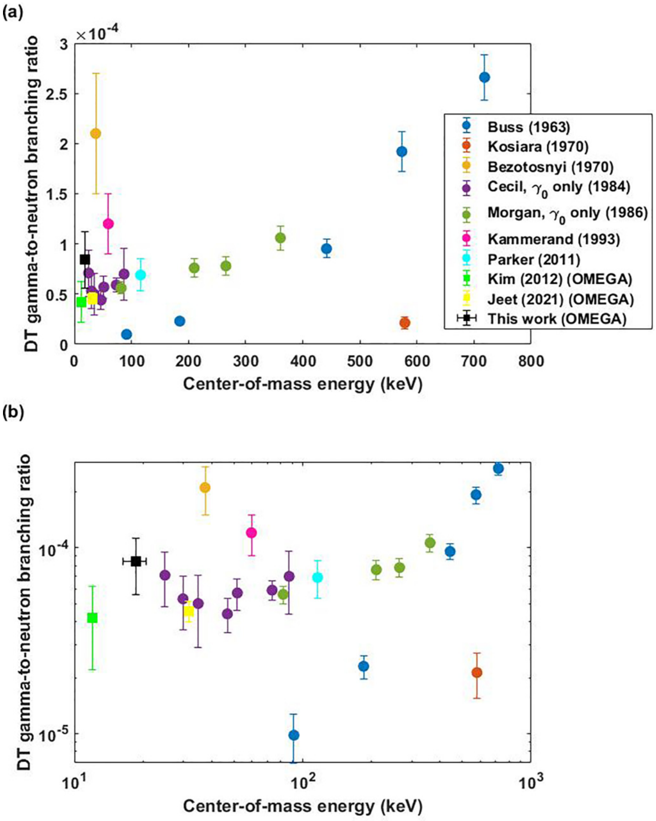

FIG. 6. Branching ratio from this work shown along with those from Refs. [2–4] and [11–17] in (a) linear and (b) logarithmic scale. Note that, even though the error bar on this measurement [i.e., $(8.42 \pm 2.84) \times 10^{-5}$] appears large in the plot, its fractional uncertainty is smaller than that of the branching ratio shown in Refs. [2] and [3] [i.e., $(4.2 \pm 2) \times 10^{-5}$]. The CM energy for the measurement inferred in this work is 19 ± 2 keV. Top image originally published in Frontiers in Physics (see Ref. [8] for full citation).

involving $D(T, \gamma)^5He$ are suspected to have background-related issues.

IV. SUMMARY AND CONCLUSION

The DT γ-to-neutron branching ratio was inferred on an ICF platform using a set of 52 cryogenic DT implosions performed at OMEGA. A quartz-based Cherenkov detector was calibrated to the carbon γ cross section $[C(n, n')\gamma]$ in order to calculate the γ yield from these experiments while neutron yields were measured using a standard nTOF detector at OMEGA. The inferred branching ratio was $(8.42 \pm 2.84) \times 10^{-5}$ where the reported uncertainty includes both systematic and statistical uncertainties.

This measurement is about a factor of two higher than the previously reported ICF-based measurement of $(4.2 \pm 2) \times 10^{-5}$ that was measured using GCD-1 with $D\,^3He$ calibration [2,3]. The two measurements are, however, in agreement with one another, as their error bars overlap. The present measurement is, however, not in agreement with the more recent and more precisely measured branching ratio from GCD-3, which reported $(4.56 \pm 0.58) \times 10^{-5}$ [4]. Assuming the recently reported $\gamma_1 : \gamma_0$ ratio of 2.1 : 1 [1], the current measurement is somewhat lower than accelerator measurements [14,15] that measured the γ_0 branch only. However, this measurement appears to be logically consistent with the accelerator measurements in that the total $\gamma_0 + \gamma_1$ is larger than the γ_0 only accelerator data, which was not the case for the GCD-based measurements.

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