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Measurement of the Gamma-Ray-to-Neutron Branching Ratio for the Deuterium-Tritium Reaction in Magnetic Confinement Fusion Plasmas

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At present, magnetic confinement fusion devices rely solely on absolute neutron counting as a direct way of measuring fusion power. Absolute counting of deuterium-tritium gamma rays could provide the secondary neutron-independent technique required for the validation of scientific results and as a licensing tool for future power plants. However, this approach necessitates an accurate determination of the gamma-ray-to-neutron branching ratio. The gamma-ray-to-neutron branching ratio for the deuterium-tritium reaction $^3\mathrm{H}(^2\mathrm{H},\gamma)^5\mathrm{He}/^3\mathrm{H}(^2\mathrm{H},n)^4\mathrm{He}$ was determined in magnetic confinement fusion plasmas at the Joint European Torus in predominantly deuterium beam heated plasmas. The branching ratio was found to be equal to $(2.4 \pm 0.5) \times 10^{-5}$ over the deuterium energy range of (80 ± 20) keV. This accurate determination of the deuterium-tritium branching ratio paves the way for a direct and neutron-independent measurement of fusion power in magnetic confinement fusion reactors, based on the absolute counting of deuterium-tritium gamma rays.

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Magnetic confinement fusion devices like ITER [1] and SPARC [2] will lead commercial fusion research for the next decades. A mixture of deuterium (^{2}H) and tritium (^{3}H) is the selected fuel to pursue this endeavor. Fusion yield, namely, the total number of deuterium-tritium (DT) reactions obtained by the machine during a discharge, serves as a key performance metric for both current experiments and future power plants.

Presently, absolute counting of the 14 MeV neutrons produced by the $^3\mathrm{H}(^2\mathrm{H},n)^4\mathrm{He}$ reactions is the only direct technique available for measuring fusion yield in magnetic confinement devices. This measurement is performed using fission chambers in combination with activation foils [3,4]. Because of the challenging nature of neutron transport, such a technique relies on extensive *in situ* calibration campaigns and detailed numerical Monte Carlo modeling of the entire machine environment [5–14]. Moreover, whenever modifications are made to the device vessel or the surrounding structures, this calibration needs to be repeated to assess the impact of the different amounts of materials on the neutron monitors.

Relying on a sole technique to assess such an important performance parameter represents a critical liability in the field. The development of a novel, direct, and neutron-independent alternative approach to fusion yield measurements is thus required to validate scientific results both in present and forthcoming experiments and for licensing purposes in future power plants.

The absolute counting of the gamma rays emitted by the less frequent $^3\mathrm{H}(^2\mathrm{H},\gamma)^5\mathrm{He}$ reaction branch is a potential candidate to fulfil this role. Because of the fewer interaction channels with matter, gamma-ray transport demands much lighter Monte Carlo modeling than its neutron counterpart. Neutron cross sections strongly vary with neutron energy,

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are not correlated with the atomic number of the material, and can significantly vary for isotopes. On the contrary, gamma-ray interactions feature cross sections that increase with the atomic number of the materials and can be better modeled and measured than the neutron ones. For this reason, absolute gamma-ray measurement on a reactor could be implemented without the need for repeated calibration campaigns if changes are made to the reactor vessel or the surrounding structures of the device. However, measuring the fusion power through absolute counting of the gamma rays requires accurate knowledge of the $^3\mathrm{H}(^2\mathrm{H},\gamma)^5\mathrm{He}/^3\mathrm{H}(^2\mathrm{H},n)^4\mathrm{He}$ branching ratio ($\mathrm{BR}_{\gamma/n}$).

In the last sixty years, several attempts were made to ascertain the $\mathrm{BR}_{\gamma/n}$. Most of them were conducted at accelerator facilities by bombarding tritiated targets with energetic deuterons [15–22]. The rest of the experiments were conducted at inertial confinement fusion facilities, where DT reactions were achieved by compressing cryogenic pellets with intense electromagnetic radiation [23–27]. In these previous studies, it was found that the $\mathrm{BR}_{\gamma/n}$ largely favors the neutron branch by approximately 5 orders of magnitude. Nevertheless, there is considerable disagreement in the available literature with a significant spread in the value of $\mathrm{BR}_{\gamma/n}$ ranging from 1.27×10^{-5} [28] to 2.84×10^{-4} [16]. A novel accurate determination of the gamma-ray-to-neutron branching ratio is therefore required to allow measurement of the fusion yield through absolute gamma-ray counting.

The Joint European Torus (JET) tokamak is the largest magnetic confinement fusion device in the world and the only one capable of operating with a DT fuel mixture. JET has recently conducted its second deuterium-tritium experimental campaign (DTE2) [29].

Significant technical enhancements of the JET tangential gamma-ray spectrometer [30–32] allowed the first determination of the DT $\mathrm{BR}_{\gamma/n}$ in a magnetic confinement fusion device: a 93 cm long lithium hydride attenuator was installed inside the detector line of sight, to reduce the 14 MeV neutron flux to the detector to suppress the neutron-induced background [33]; the data collection system was improved using a fast digital acquisition module to allow for continuous sampling and to avoid dead time. Finally, the spectrometer absolute detection efficiency was determined using a novel technique that takes advantage of the intrinsic background radioactivity of the $^{138}\mathrm{La}$ naturally present inside the $\mathrm{LaBr_3{:}Ce}$ scintillator crystal [34].

Assessment of the fusion yield by absolute gamma-ray counting takes advantage of the less frequent branch of the deuterium-tritium reaction. Fusion of the DT reactants produces an excited $^5\mathrm{He}$ nucleus that predominantly decays from the resonance level ($J^\pi = 3/2^+$) to the $^4\mathrm{He}$ ground state through the emission of a 14 MeV neutron. Alternatively, it can deexcite to either the $^5\mathrm{He}$ ground state ($J^\pi = 3/2^-$) or to the first excited state ($J^\pi = 1/2^-$) via an electric dipole radiative decay. These two lower levels of $^5\mathrm{He}$ are unbound with respect to $^4\mathrm{He}+n$ and have, therefore, significant widths. The two radiative transitions result in the emission of non-monoenergetic gamma rays that are respectively referred to as γ_0 and γ_1. These two gamma rays have broad spectral profiles, peaking at approximately 16.7 MeV and 14.2 MeV, correspondingly.

The $\mathrm{BR}_{\gamma/n}$ was determined from simultaneous measurement of the yield of these two gamma rays ($Y_{\gamma0}$ and $Y_{\gamma1}$) and of the 14 MeV neutrons (Y_n) for a selection of 89 JET DTE2 discharges as

$$\mathrm{BR}_{\gamma/n} = \frac{Y_{\gamma0}+Y_{\gamma1}}{Y_n} = \frac{Y_\gamma}{Y_n}. \tag{1}$$

Presently, at JET the neutron yield is primarily measured using fission chambers cross-calibrated with activation foils. Since fission chambers are also sensitive to 2.5 MeV neutrons emitted by $^2\mathrm{H}(^2\mathrm{H},n)^3\mathrm{He}$, additional information from single crystal diamond neutron spectrometers was used to determine the 14 MeV neutron yield for low tritium concentration discharges, where the 2.5 MeV neutron background contribution was significant and had to be corrected for [35]. The JET neutron monitors are absolutely calibrated and can provide the 14 MeV neutron yield Y_n within a ±7% uncertainty [14].

During DTE2, the gamma-ray yield Y_γ was measured using the improved JET tangential gamma-ray spectrometer. The detector consists of a $3'' \times 6''$ $\mathrm{LaBr_3{:}Ce}$ scintillator crystal coupled to a photomultiplier tube. The instrument is positioned at 19.7 m from the machine port, along a collimated tangential line of sight (see Fig. 1) and the measurements are not toroidally localized. The gamma-ray spectrum integration time was in the range of 5 to 10 sec, depending on the duration of the discharge.

The total number of γ_0 or γ_1 events detected by the spectrometer between the energies E_1 and E_2 is given by

$$\int_{E_1}^{E_2} C_{\gamma i}(E)dE = Y_{\gamma i}\Omega \int_{E_1}^{E_2} S_{\gamma i}(E) * T(E) * R(E)dE, \tag{2}$$

where $i = 0, 1$ indicates either the γ_0 or γ_1 radiative decay, $C_{\gamma i}(E)$ is the number of events per unit of energy in the measured spectrum for the γ_i transition, $Y_{\gamma i}$ is the associated absolute gamma-ray yield, Ω is the fraction of the emitted gamma rays intercepted by the line of sight, $S_{\gamma i}(E)$ is the normalized non-monoenergetic radiative decay spectrum per unit of energy, $T(E)$ represents the gamma-ray transmittance through the materials along the detector line of sight, such as the lithium hydride attenuator, per unit of energy, and $R(E)$ is the detector response function, including its absolute gamma-ray detection efficiency, per unit of energy.

The normalized non-monoenergetic radiative decay spectrum $S_{\gamma i}(E)$ is determined using the R-matrix technique [36]. The properties of the $^5\mathrm{He}$ energy levels used for the analysis are given in Ref. [37].

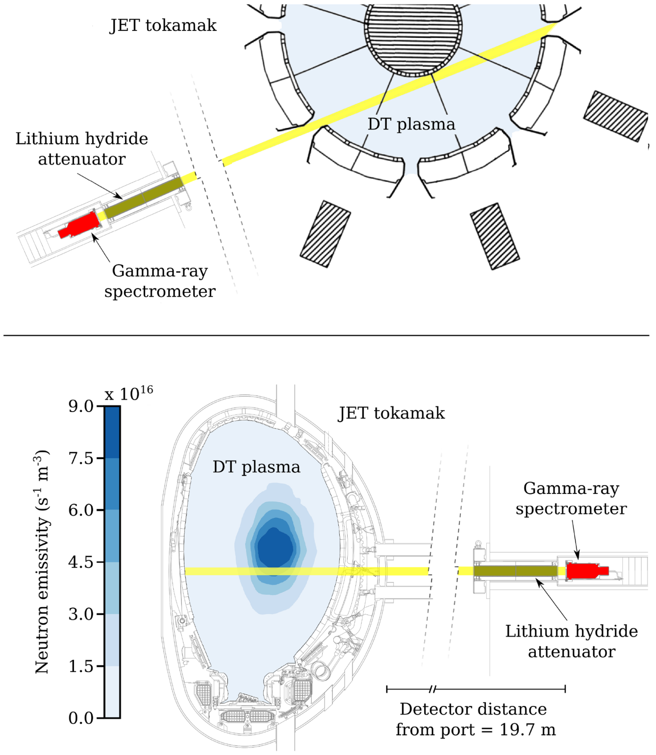

FIG. 1. A schematic of the JET tangential gamma-ray spectrometer line of sight. The top-down view is depicted in the upper half, while the poloidal cross-section is shown in the bottom half. The detector and the attenuator are illustrated in the top left and bottom right parts of the figure. The bottom left section illustrates the poloidal section of the machine, including a tomographic reconstruction of a typical neutron emission profile measured with the JET neutron camera.

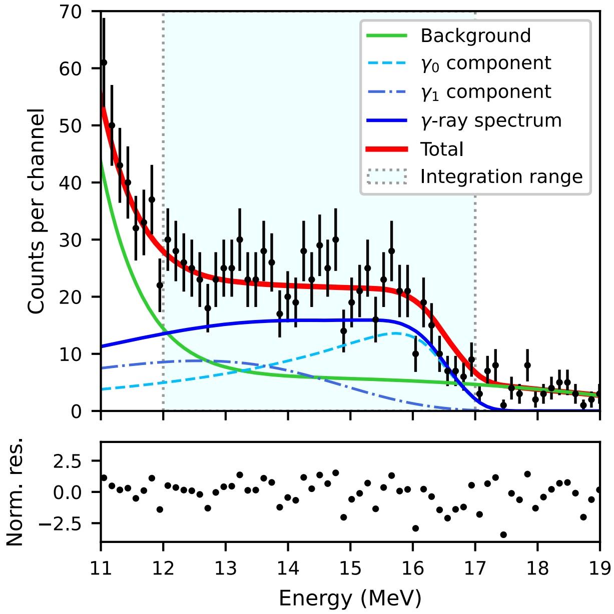

FIG. 2. The top section presents the gamma-ray pulse height spectrum measured in a single JET DT discharge (JPN 99664). It illustrates the total fit of the data along with its gamma-ray and background components. The normalized residuals are presented in the bottom section. The fit reduced χ^2 is equal to 1.27.

Since the JET plasma is an extended gamma-ray source with respect to the detector line of sight, the Ω term takes into account both the gamma-ray optical transport and the nonuniform volumetric emission from the plasma. The DT gamma-ray emission features a radial profile, and it is toroidally symmetric. This characteristic is due to the strong axisymmetric property of the tokamak magnetic configuration that holds true in steady-state configurations. Tomographic reconstructions of the 14 MeV neutron emission were performed using the data collected by the JET neutron camera for each of the plasma discharges in the dataset [38]. The DT gamma-ray emission was considered to retain the same profile as the one for the 14 MeV neutrons, under the assumption that the $\mathrm{BR}_{\gamma/n}$ does not depend on the energy of the reactants. This assumption is justified by the fact that, at the energies achieved at JET, DT reactions are strongly dominated by the $J^\pi = 3/2^+$ resonance [24].

The Monte Carlo N-particle nuclear transport code (MCNP) was used to assess the gamma-ray transport through a detailed model of the detector line of sight [39,40]. The MCNP results for the optical transport Ω were also independently validated using semianalytical calculations [41,42]. The two estimates agree within a 1% deviation. We note that only a small fraction (10^{-3}) of gamma rays are nondirect. In addition, MCNP was used to determine the gamma-ray transmittance through the materials along the detector line of sight $T(E)$ and the detector response function $R(E)$. The absolute efficiency of the detector was validated using the intrinsic background radioactivity of the ^{138}La inside of the scintillator crystal and its nominal volume. It was found to agree with the MCNP model within a 0.07% error margin [34].

The details of the γ_0 and γ_1 line shapes and of the background component were investigated from the total gamma-ray spectrum obtained by combining the data from the selected JET DTE2 discharges. This analysis has determined the best description for the background in the region of interest, and relative intensities of the background, γ_0 and γ_1 components. Furthermore, the $Y_{\gamma 0}/Y_{\gamma 1}$ branching ratio was ascertained [43].

A typical pulse height spectrum measured in a single JET DT discharge is shown in Fig. 2. The energy calibration was performed using the gamma-ray lines from the neutron inelastic scattering on ^{58}Ni (1.454 MeV) [44], neutron capture on ^{58}Ni (8.533 MeV, 8.998 MeV) [45], and neutron capture on ^{53}Cr (9.719 MeV) [46]. This background is expected at JET since nickel and chromium are present in the alloys of the vacuum vessel and in the detector line of sight components [47]. The calibration was improved in the high energy range exploiting the characteristic shape of the γ_0 decay. This latter correction corresponds to an upward scaling of the energies approximately equal to 1.5% at 17 MeV.

The calibrated pulse height spectrum was fitted with a model to separate the gamma-ray signal from the background contribution, as shown in Fig. 2 [43]. The total gamma-ray component is the scaled sum of the $S_{\gamma i}(E)$ normalized non-monoenergetic radiative decay spectra convolved with the detector response function $R(E)$, shown as dashed curves. The absolute gamma-ray yields Y_{γ_0} and $Y_{\gamma 1}$ are then derived from Eq. (2) as

$$Y_{\gamma i} = \int_{E_1}^{E_2} C_{\gamma i}(E) dE \Big/ \left(\Omega \int_{E_1}^{E_2} S_{\gamma i}(E) * T(E) * R(E) dE \right) \tag{3}$$

where E_1 and E_2 were chosen to be, respectively, 12 MeV and 17 MeV. This region corresponds to the energy range where the total gamma-ray signal is more intense than the background component. The total DT gamma-ray yield $Y_\gamma = Y_{\gamma 0} + Y_{\gamma 1}$ was computed for all discharges in the dataset using Eq. (3).

The relationship between the measured absolute total gamma yield Y_γ and the absolute 14 MeV neutron yield Y_n is linear, as can be seen in Fig. 3. The ratio between these two values is the gamma-ray-to-neutron branching ratio for the DT reaction $\mathrm{BR}_{\gamma/n}$. Relative uncertainties on Y_n are taken to be the nominal value of 7% provided by JET [14]. Uncertainties on Y_γ shown in Fig. 3 include only contributions of statistical origin related to uncertainties on $C_{\gamma i}$ and on the $Y_{\gamma 0}/Y_{\gamma 1}$ branching ratio [43]. The average relative uncertainty on the value of Y_γ is equal to 12.8%. The linear relationship between Y_γ and Y_n shows a constant DT $\mathrm{BR}_{\gamma/n}$ with a value equal to $(2.4 \pm 0.3) \times 10^{-5}$. The primary sources of systematic uncertainty are tied to the determination of the background fraction, the amount of material present in the line of sight, and the tomographic reconstruction of the neutron emission profile. By including these systematic uncertainties the value for the DT branching ratio is $(2.4 \pm 0.5) \times 10^{-5}$. A summary of the primary causes of uncertainty and their relative contribution to the final BR variance can be found in Table I.

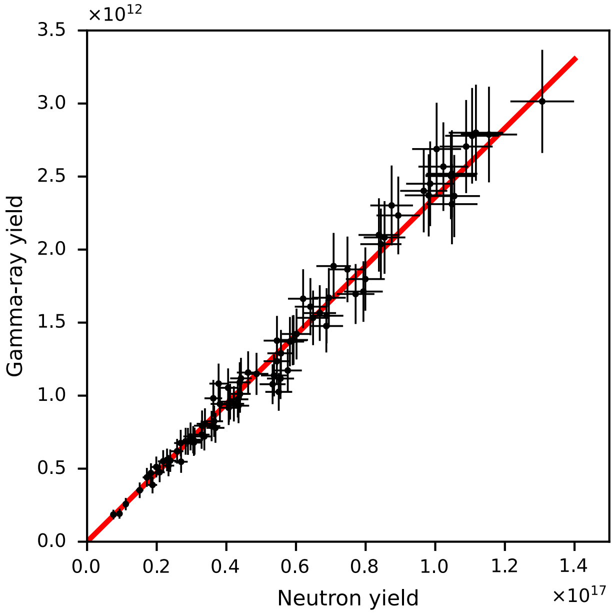

FIG. 3. Absolute fusion gamma-ray yield as a function of the absolute neutron yield. The slope of this linear relationship represents the gamma-ray-to-neutron branching ratio for the DT reaction.

Conventionally, the value of the gamma-ray-to-neutron branching ratio for the DT reaction is presented against the energy of the deuteron in the triton reference frame. For beam-on-target experiments, this is equivalent to the energy of the deuteron beam in the laboratory coordinate system. The JET DT reactions that occurred in the analyzed discharges were predominantly generated by deuterium neutral beam injection which, after being ionized, interacts with the bulk tritium ions previously puffed into the vacuum chamber [34]. Neutral beam injection is a form of external plasma heating commonly used in magnetic confinement fusion where fuel atoms are initially ionized outside the vessel, accelerated via an electrostatic field to energies in the order of several tens of keV, and, finally, neutralized so that they may penetrate the magnetic field of the tokamak. These neutral fast particles enter into the vacuum vessel and collide with the plasma. During these collisions, they are once again ionized and remain confined inside the tokamak where they can transfer their energy through further interactions with the plasma. Upon ionization, particles are uniformly dispersed in the toroidal direction within a few microseconds, maintaining the axisymmetric property of the deuterium-tritium gamma-ray emission.

Deuterium was the sole injected fuel in all the selected plasma discharges with an injected energy ranging from 95 to 115 keV. The individual values of the branching ratio computed for each discharge were all in agreement within the error bars and did not show any significant correlation with the deuterium injected energy. The energy distribution function for a deuteron incurring in a DT reaction during

TABLE I. Summary of primary uncertainties contribution to the final value of the DT gamma to neutron branching ratio. The acronym ROI stands for region of interest and represents the energy interval from 12 to 17 MeV.

Uncertainty	Relative weight in the final BR variance
Background description	71.00%
Fraction of γ_1 in ROI	24.78%
Attenuation of γ_1	1.9%
Attenuation of γ_0	1.79%
Fraction of γ_0 in ROI	0.29%
Neutron yield	0.12%
Gamma counts in ROI	0.10%
Optical transport	0.02%

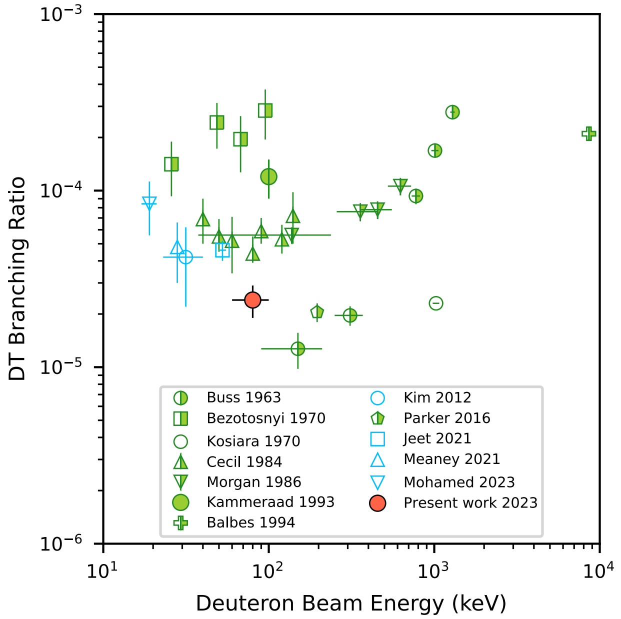

FIG. 4. Measured values of the $\mathrm{BR}_{\gamma/n}$ for the DT reaction from accelerator facilities (green), inertial confinement fusion (blue) and magnetic confinement fusion (red). Empty markers represent current-based measurements, half-full markers denote spectroscopic measurements for γ_0 only, and full markers indicate spectroscopic findings including both γ_0 and γ_1.

these discharges has an average value of 80 keV. The interval (80 ± 20) keV covers 68% of the energy distribution function and it has been chosen as the uncertainty range for the equivalent deuterium beam energy.

The results presented in this Letter provide a new and reliable value of the DT gamma-ray-to-neutron branching ratio based on direct spectroscopic measurements. It is worthwhile to compare this finding with all previous measurements obtained at accelerators or inertial confinement fusion facilities in the last sixty years. The results found in the literature (see Fig. 4) display a significant spread. This is true even at deuteron beam energies less than 100 keV, where the $J^{\pi} = 3/2^{+}$ resonance dominates the fusion process. The accurate assessment of $\mathrm{BR}_{\gamma/n}$ is complicated by several elements such as the neutron-induced background, the knowledge of γ_0 and γ_1 spectral lines, the determination of the absolute detector efficiency, and instrumental effects. The present work has addressed and identified solutions for all these issues [43,48].

We observe that the most recent measurements at inertial confinement fusion provide higher branching ratio values in the range of factor 2 to 3.5 with respect to the present work [24–27]. Of these works, only Kim *et al.* (2012) is compatible with the present result within the reported uncertainties.

Gamma-ray spectroscopy is the key allowing for precise determination of the γ_0 and γ_1 signals and of the background. At present, this technique can be adopted only at continuous fusion sources, such as accelerator experiments and magnetic confinement fusion devices, where the detection of individual gamma-ray events can be achieved. At inertial confinement fusion experiments, the entire gamma-ray signal is produced on the timescale of the pellet implosion, i.e., of the order of one nanosecond [23]. This fast timescale only allows for measurement of the signal intensity above a fixed energy threshold. Assessing the signal adherence to the semiempirical R-matrix predictions, the $Y_{\gamma1}/Y_{\gamma0}$ ratio, and the background level within the region of interest is, therefore, challenging. Differences in the reported values of the branching ratio could be attributed to discrepancies in these quantities. On the other hand, the gamma-ray spectroscopy technique adopted in the present work allows for a quantitative assessment of the signal adherence to the semiempirical R-matrix predictions, the $Y_{\gamma1}/Y_{\gamma0}$ ratio, and the background level, thus improving confidence in the final result.

It is interesting to observe that all spectroscopic gamma-ray measurements conducted at accelerators included only γ_0 in their analysis, with the exception of Kammeraad *et al.* (1993) [20]. When compared to the results of Kammeraad *et al.*, the value of $\mathrm{BR}_{\gamma/n}$ found in this work is about 5 times lower. Relative to this previous study, the present work benefits from significant technological developments. These include the adoption of fast digital data acquisition, featuring zero dead time and full waveform streaming, enabling loss-free event collection, and an improved gamma-ray scintillator material (LaBr3:Ce), which features a better energy resolution and is approximately 14 times faster than NaI. These technical advancements allow for greater robustness against pileup and spectral distortions. The present measurement also benefits from a thicker neutron attenuator (93 cm of LiH compared to 58 cm of boron-loaded polyethylene) that features a 5 times higher neutron flux attenuation. Noticeably, the measured spectrum features a lower background with respect to Kammeraad *et al.* especially in the region of interest between 12 and 17 MeV. Finally, we note that in their analysis Kammeraad *et al.* use the gamma-ray spectrum measured from the mirror reaction $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ to interpret the deuterium-tritium data. Instead, in this Letter, we used the $^{5}\mathrm{He}$ γ_0 and γ_1 spectral lines computed using the R-matrix technique.

The first measurement of the DT $\mathrm{BR}_{\gamma/n}$ obtained from magnetically confined plasmas is direct proof that absolute gamma-ray counting can be a reliable and neutron-independent technique to ascertain fusion yield in tokamaks. This addresses a critical problem for next-generation experiments that aim to demonstrate net energy gain, like ITER and SPARC, by providing an independent technique to validate fusion performances. Furthermore, this detector system, with its low footprint and limited need for extensive *in situ* calibration campaigns, offers great potential for real-time fusion power measurement in forthcoming commercial reactors, where a secondary neutron-independent measure of fusion power will be an invaluable tool for licensing and safe operation.

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