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First direct measurement of the spectrum emitted by the $^3H(^2H,\gamma)^5He$ reaction and assessment of the relative yield γ_1 to γ_0

Marica Rebai [1] Davide Rigamonti [1] Andrea Dal Molin [1,*] Giulia Marcer [2] Angela Bracco [3] Franco Camera [3] Daniela Farina [1] Giuseppe Gorini [1,2] Evgeniy Khilkevitch [4] Massimo Nocente [1,2] Enrico Perelli Cippo [1] Oscar Putignano [1] Jimmy Scionti [1] Alexander Shevelev [4] Andrej Zohar [5] and Marco Tardocchi [1]

[1] Institute for Plasma Science and Technology, Consiglio Nazionale delle Ricerche, Via Cozzi 53, 20125 Milan, Italy
[2] University of Milano Bicocca, Piazza della Scienza 3, 20126 Milan, Italy
[3] University of Milano, Via Celoria 16, 20133 Milan, Italy
[4] Scientist from St. Petersburg 190000, Russian Federation
[5] Reactor Physics Department, Jozef Stefan Institute, 1000 Ljubljana, Slovenia

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The spectral γ ray emission from the reaction $^3H(^2H,\gamma)^5He$ has been measured for the first time in a magnetic confinement deuterium-tritium plasma experiment at the Joint European Torus. A custom developed gamma ray spectrometer system based on a $LaBr_3$ scintillator combined to a LiH neutron attenuator and a zero dead time fast digital data acquisition allowed to measure the weak γ ray emission under the $\approx 10^5$ more intense 14 MeV neutron field. The R-matrix analysis of the ^5He nucleus has been used to predict the expected gamma ray spectrum which has been compared with the measurement, but cannot predict the relative intensity of the γ lines. The data analysis has identified the energy and width of the known 16.75 MeV γ ray emission (γ_0), from the second excited state to the ground state of the formed ^5He nucleus, and confirmed the presence of a second emission (γ_1) at $\approx$ 14 MeV due to the transition from the second to the first excited state. The analysis has shown that the γ_1 emission is broad and has assessed for the first time in a magnetic confinement experiment the relative yield γ_1 to γ_0 equal to 1.09 ± 0.25.

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I. INTRODUCTION

One of the approaches towards electricity production from nuclear fusion is to magnetically confine two hydrogen isotopes, deuterium (^2H or D) and tritium (^3H or T), in the state of plasma in a toroidal chamber named *tokamak* and to heat the plasma at temperatures above $\approx$ 10–20 keV to make the fusion reactions probable to happen. Fusion reactions between D and T ions produce a $^5He^*$ nucleus in the second excited state which predominantly decays into a neutron and an α particle (or ^4He),

$$^5He^* \rightarrow {}^4He(3.5\,\mathrm{MeV}) + n(14.1\,\mathrm{MeV}). \quad (1)$$

Being charged, the ^4He remains confined in the plasma and actively participates to the self-sustainment of the fusion process; on the other hand the neutron escapes and it can be used to monitor the fusion reaction rate. In particular, one of the main parameters that can be measured is the 14 MeV neutron yield that is directly related to the fusion power [1]. Alternatively, as depicted in Fig. 1, ^5He can decay via an electromagnetic channel with a branching ratio which is poorly known in the literature. The measured values vary in the range from about 1.2×10^{-4} to 5.6×10^{-5} [2,3]. In the electromagnetic channel the ^5He decays emitting γ rays:

$$\begin{aligned} ^5He^* &\rightarrow {}^5He + \gamma_0 \\ &\rightarrow {}^5He + \gamma_1. \end{aligned} \quad (2)$$

Here, γ_0 is emitted when the resonant state at E_2 directly de-excites to the ground state at $E_{g.s.}$, while γ_1 is emitted when the decay goes through the intermediate state at E_1. Although the existence of these two γ rays is predicted by nuclear theory, the experimental verification of the γ ray spectrum arising from $^5He^*$ decay has been mainly based on the observation of the mirror reaction $D + {}^3He \rightarrow {}^5Li^*$. The latter de-excites with at least three branches giving rise to a peak centered at 16.66 MeV (width of 1.5 MeV) and a broader peak placed at about 14 MeV (width between 3 − 7 MeV):

$$\begin{aligned} ^5Li^* &\rightarrow {}^4He + p \\ &\rightarrow {}^5Li + \gamma_0 \\ &\rightarrow {}^5Li + \gamma_1. \end{aligned} \quad (3)$$

The broadening of these γ ray lines is due the ^5Li unbound nature. Since the main channel emits protons, in traditional beam-on-target experiments it is possible to measure the γ ray spectrum quite clearly without the strong background induced by neutrons [4,5].

The DT reaction involving the ^5He is expected to show a spectrum similar to the D^3He reaction. The measurement

*Contact author: andrea.dalmolin@istp.cnr.it

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efforts dedicated to the direct observation of γ_1 are strongly affected by the intense 14 MeV neutron background covering the weak γ ray signal [6], resulting in large discrepancies about the existence of the γ_1 and, in those cases when it has been detected, about its energy, width [7,8,9] and relative intensity [6,10]. The first measurement of the relative intensity of γ_0 and γ_1 has been recently achieved in inertial confined DT experiments at NIF [10] where, due to the short duration of the DT implosion (<1 s), neutrons can be discriminated against gamma rays with the time-of-flight technique. The ^{5}He* energies of the γ_0 and γ_1 gamma ray lines have been measured at 16.75 MeV and 12.5 MeV, respectively. The γ ray line shapes were calculated from the *R*-matrix analysis and a relative ratio Γ_1/Γ_0 of $(2.1 \pm 0.4) : 1$ was found compatible with the measurement [10].

In this work we present the first direct measurement of the γ ray spectrum of the ^{3}H(^{2}H, γ)^{5}He fusion reaction in magnetic confined plasmas and the comparison to the *R*-matrix prediction. The measurements were carried out at the Joint European Torus (JET) in Culham, United Kingdom, during the deuterium-tritium campaign held in fall 2021 (DTE2). The measurement employed a lanthanum bromide scintillator detector combined with a fast digital data acquisition installed on a collimated and shielded line of sight. Besides this introduction, the paper is organized in three sections. Section II is dedicated to the experimental setup and calibrations, while Sec. III describes the data analysis which provides the γ ray spectrum and the γ_1 and γ_0 relative intensities. The latter is essential for quantifying the gamma rays emitted during the fusion process in tokamaks and, thus, could be of interest in the forthcoming fusion reactors, like ITER, as a second neutron-independent method to measure the fusion power. Finally, the conclusions are presented in Sec. IV.

II. EXPERIMENTAL

Three lanthanum bromide ($LaBr_3$) γ ray spectrometers have been installed in the last decade at JET to measure γ ray spectra above 1 MeV mainly for physics studies of energetic ions [11]. One of them, the γ ray diagnostic KM6T (see Fig. 2), is installed on a tangential line of sight at a distance of about 20 m from the machine vessel. γ rays produced in the plasma core travel in a set of collimators towards the 93 cm long LiH attenuator, whose role is to suppress the direct 14 MeV neutron flux [12], behind which the KM6T diagnostic is placed. KM6T is based on a 3 in. × 6 in. cylindric $LaBr_3$ crystal coupled to a photomultiplier tube (PMT) equipped with an active voltage base able to work at high counting rates in excess of several hundreds of kHz [13–15]. The detector is also equipped with two reference LED pulse signals which are used as a monitor of the PMT gain shift which happens at high counting rates during the JET DT discharges. During the JET DTE2 campaign the analog signals from the PMT were digitized with a custom data acquisition based on the National Instrument digitizer NI5772 operated for 100 s in continuous streaming mode with a sampling rate of 200 MHz, without dead times. Each stored 100 s long detector pulse is analyzed offline with a custom made algorithm developed to identify the γ ray events and their arrival time and pulse height. The algorithm employs a novel approach to correct the digitized waveform for PMT gain changes by using the reference LED signals and to recognize/recover the piled-up events [16,17]. The pulse height reconstruction algorithm has been successfully validated both with (i) synthetic waveforms sampled from a known distribution and (ii) by showing that the reconstruction of γ ray spectra measured at low and high count rate are the same.

The selected JET discharges used for the analysis belong to two different DT plasma scenarios where the KM6T diagnostic showed stable and reliable operations: (i) tritium percentage below 5 %, or (ii) external heating power below 10 MW. Both scenarios are characterized by a total neutron yield below 10^{17} n/s. The reconstructed pulse height spectra are summed together in order to enhance the statistic for a detailed analysis of the spectral shape. The sum of pulse height spectra (see Fig. 3) shows several peaks up to 10 MeV, due to neutron interactions with the environmental materials surrounding the detector. Among these it is possible to identify neutron inelastic reactions in the steel pipe at energies equal to 1.454 MeV and neutron captures reactions at 8.533 MeV and 8.998 MeV besides 9.719 MeV due to reactions with Ni^{58} and Cr^{53}, respectively [18]. These lines, despite being background signals, provide an assessment of

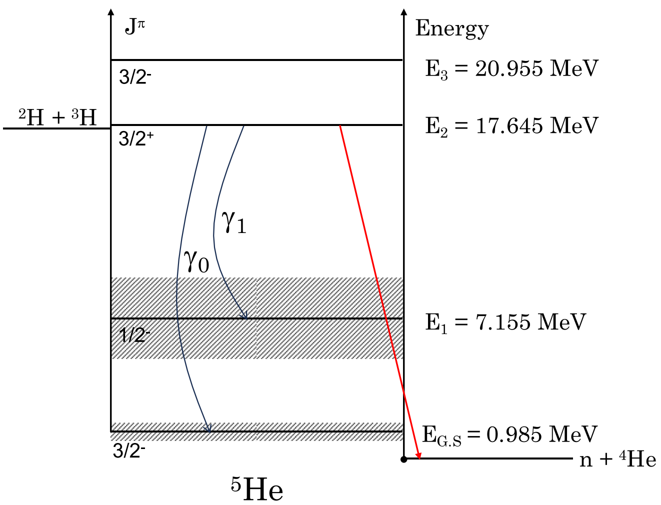

FIG. 1. First energetic levels of the unbound ^{5}He nucleus produced in a ^{3}H(^{2}H, γ)^{5}He fusion reaction and associated decay scheme. Energy levels are referred to the final $n + {}^4$He state. Data are taken from [4].

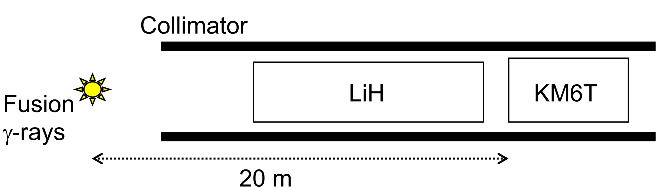

FIG. 2. Schematic of the JET KM6T γ ray diagnostic used for these measurements. A $LaBr_3$ scintillator is installed along a collimated line of sight which is filled with a LiH neutron attenuator. The drawing is not to scale.

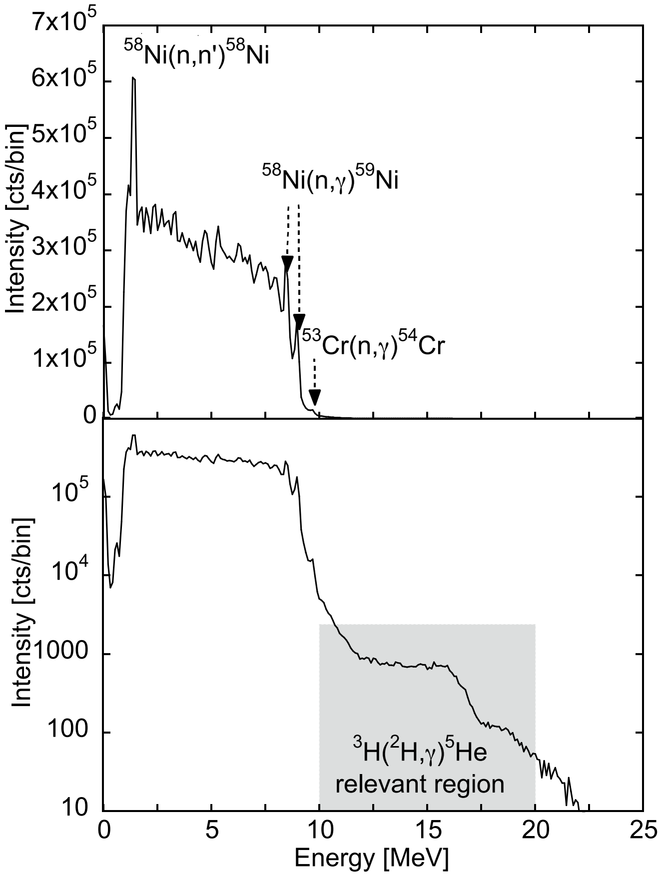

FIG. 3. Sum of pulse height spectra measured with the KM6T diagnostic during the selected JET discharges in linear (top) and logarithmic scale (bottom). Three (n, γ) peaks used for calibrations are indicated together with the relevant region for the measurement (in grey).

the good detector spectroscopic capabilities and are used as reliable energy-calibration points. A parabolic calibration curve has been employed and despite the quadratic term is found to be small (about 10^{-5} MeV^{-2}), the wide range of gamma ray energies (0–20 MeV) involved implies that reliable nonlinear calibration curves must be used. The region relevant for the DT fusion γ rays covers the range between 10 and 20 MeV and represents a minority fraction (10^{-4}) of the total collected events (as evident in the logarithmic scale plot Fig. 3).

The detector response function, $R(E)$, has been simulated with the Monte Carlo code MCNP6 [19] in the energy range of 0.1–30 MeV (in steps of 100 keV), broadened with a gaussian function whose full width at half-maximum (FWHM) was taken equal to 150 keV at 16.7 MeV. Simulations were also independently performed with the GEANT4 code and provided similar results within 1 %. The expected detector response to γ rays can be obtained by convolving the incoming gamma ray spectrum with $R(E)$. Ideally, when the detector is irradiated with a monoenergetic 16.7 MeV γ ray beam (see Fig. 4 top panel) the characteristic structures relative to the full-energy, single escape, and double escape peaks can be observed together with their Compton edges. Since the energy of the γ rays is much higher than 1 MeV, and the $LaBr_3$ is

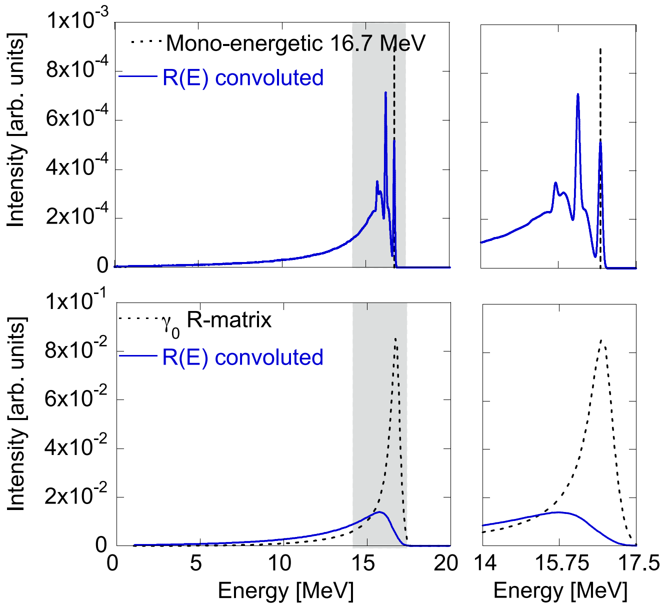

FIG. 4. Simulations of the predicted detector response to incoming gamma ray spectra. The simulations consist of the convolution of either a monochromatic 16.75 MeV gamma ray beam (top left panel) or the R-matrix calculated γ_0 line (bottom left panel) with the detector response function [$R(E)$]. The grey boxes indicates the region between 14.0 and 17.5 MeV and the same plots zoomed in this region are shown in the right panels.

an high-density and large-size crystal, the intense contribution due to pair-production is clearly visible. Conversely, the simulated detector response to γ_0 is a single broad peak centered at about 16 MeV. This is due to the fact that the expected incoming γ_0 spectral shape, calculated following the R-matrix theory [4,8,20], is a broad peak centered at 16.75 MeV and about 1 MeV wide (see Fig. 4 bottom). This implies that the broadenings, due to the detector energy resolution and to the plasma ions kinetic energies, are negligible with respect to the intrinsic broadening of the emitted γ ray lines.

III. DATA ANALYSIS

To determine the shape and relative intensity of γ_0 and γ_1, a detailed analysis of the measured energy spectrum has been performed in the region of interest between $E_1 = 10$ MeV and $E_2 = 20$ MeV. The pulse height spectrum, $M_t(E)$, has been analyzed with a PYTHON script which evaluates the intensities of the two γ rays, I_{γ_0} and I_{γ_1}, and the background shape and intensity, $B(E)$:

$$M_t(E) = I_{\gamma_0} M_{\gamma_0}(E) + I_{\gamma_1} M_{\gamma_1}(E) + B(E). \tag{4}$$

Here, the measured spectral shape of each γ, M_{γ_i} (with $i = 0, 1$), has been obtained by convolving the plasma emitted γ ray spectrum, S_{γ_i}, with the transport factor, $T_i(E)$, and the detector response function, $R(E)$:

$$M_{\gamma_i}(E) = S_{\gamma_i}(E) * T_i(E) * R(E). \tag{5}$$

The R-matrix model of ^{5}He nuclei is employed to calculate S_{γ_i}. It takes as input the resonance radius and the energy levels of the ^{5}He [4] and gives as output the spectral shapes of both γ_0 and γ_1. However, the *R*-matrix analysis does not predict the relative intensities of the γ_0 and γ_1 lines. The transport factor, $T_i(E)$, is evaluated with an MCNP6 model [21] that contains the entire JET geometry, from the vessel to the detector components, including the attenuation from materials in the line of sight and it has been validated with semianalytic calculations [22]. The total yield of γ_i, defined as Y_{γ_i}, is determined as

$$Y_{\gamma_i} = \frac{I_{\gamma_i}\int_{E1}^{E2} M_{\gamma_i}(E)dE}{\int_{E1}^{E2} S_{\gamma_i}(E)*T_i(E)*R(E)dE}, \tag{6}$$

where I_{γ_i} is inferred from the fit to the data with Eq. (4). The total γ ray yield Y_γ is equal to $Y_{\gamma_0} + Y_{\gamma_1}$.

The background contribution has been modelled with two components as

$$B(E) = b_1 e^{-b_2 E} + b_3 E^2 + b_4 E + b_5. \tag{7}$$

At deposited energies below 15 MeV it features an exponential behavior while at higher energies, $E_\gamma > 17.5$ MeV, the background is well described with a parabolic curve. The fit has seven free parameters, five of them describe the background while two of them are the intensities, I_{γ_0} and I_{γ_1}, of the two γ rays of Eq. (4).

A good agreement between the data and the model has been found (see Fig. 5). The fit residuals shown in Fig. 5 (bottom) prove the absence of systematic structures and gives a minimum reduced chi-squared χ^2_R equal to 1.60. The relative intensity of the two γ rays (Γ_1/Γ_0) can be extracted directly from Eq. (6) into the expression

$$\frac{\Gamma_1}{\Gamma_0} = \frac{Y_1}{Y_0} = \frac{I_{\gamma_1}\int_{E_1}^{E_2} M_{\gamma_1}(E)dE}{I_{\gamma_0}\int_{E_1}^{E_2} M_{\gamma_0}(E)dE} \times \frac{\int_{E_1}^{E_2} S_{\gamma_0}(E)*T_0(E)*R(E)dE}{\int_{E_1}^{E_2} S_{\gamma_1}(E)*T_1(E)*R(E)dE}, \tag{8}$$

where the first term represents the ratio of the recorded counts from γ_1 and γ_0, between E_1 and E_2, while the second term is the probability that the emitted γ rays from the plasma reach the $LaBr_3$ crystal and are detected. The relative intensity of the two γ rays has been evaluated to be $\Gamma_1/\Gamma_0 = 1.09$:1.

In order to confirm this value and to give an estimation of the statistical error bar, an analysis of the dependance of the χ^2 on Γ_1/Γ_0 has been performed. The χ^2 distribution has been calculated for a set of 16 fixed Γ_1/Γ_0 values and letting the remaining variables (background and total intensity) as free parameters (see Fig. 6). The found χ^2 distribution features a parabolic-like behavior, and can be used to find an estimation of the statistical uncertainty on Γ_1/Γ_0 [23]. This is done by varying the minimum χ^2 of 139.4 plus one which provides a statistical error of 0.17. A systematic uncertainty equal to 0.18, mainly due to line of sight attenuation and detection efficiency, has to be added. The analysis performed provides a final value of Γ_1/Γ_0 equal to (1.09 ± 0.25):1. With this value the resulting spectral shape of the γ ray emission from the ^{5}He is shown in Fig. 7.

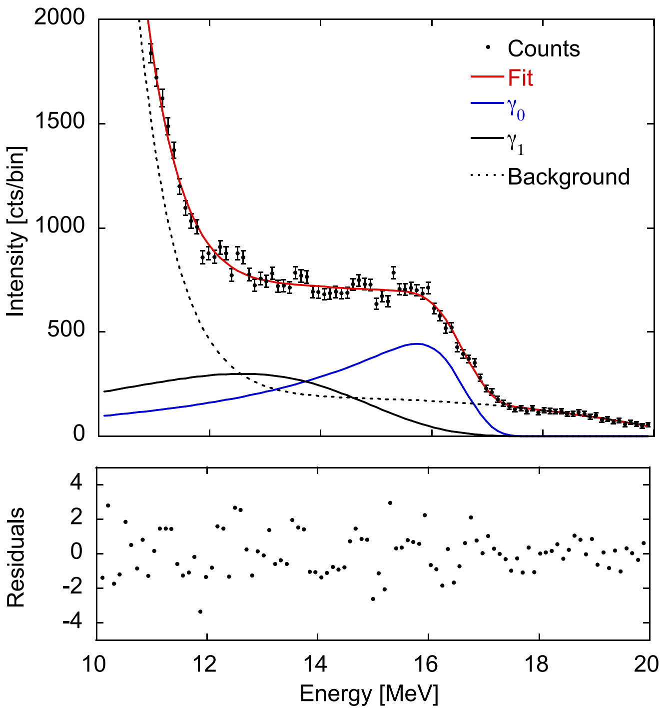

FIG. 5. Sum of pulse height spectra for the selected JET discharges shown in the ^{3}H(^{2}H, γ)^{5}He relevant region. Data are shown with statistical error bars in black dots, while the lines represent the fit components. In blue the contribution due to γ_0, in black the contribution due to γ_1, the dashed line is the background component and the red line represents their sum. Bottom panel shows the fit residuals.

The *R*-matrix analysis does not provide any prescription on the intensity of the γ_1 and γ_0 lines. The measured Γ_1/Γ_0 value can be compared with the published values in literature, summarized in Table I. We observe that the value of $\Gamma_1/\Gamma_0 =$

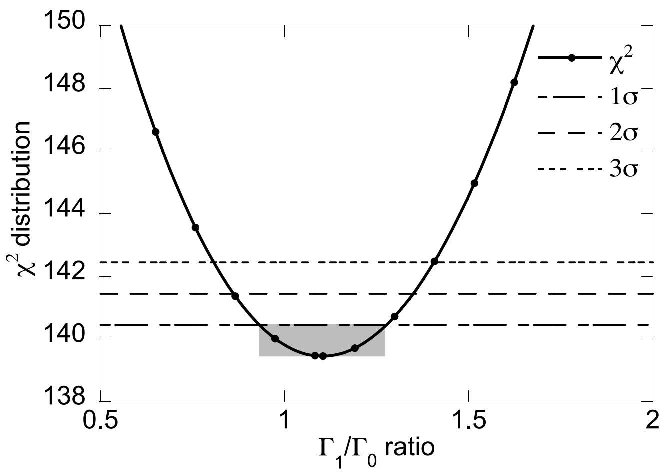

FIG. 6. Chi-square (χ^2) distribution resulting from the fit of the data as a function of the Γ_1/Γ_0 ratio. The dashed lines represent the regions in which the minimum χ^2 increases of 1, 2, and 3, i.e., error bars of 1σ, 2σ and 3σ, respectively. The grey box indicates the region in which χ^2 increases less than 1.

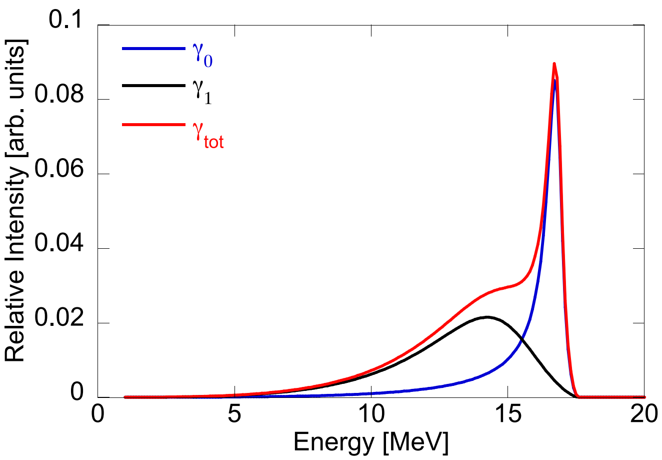

FIG. 7. γ ray spectrum emitted from the ^{5}He* nucleus.

1.09 ± 0.25 found in this work is in good agreement within one standard deviation with the ones measured in beam-on-target experiments with the D^{3}He mirror reaction in Refs. [6] and [5]. In the D^{3}He mirror reaction, the ^{5}Li is expected to feature a γ ray spectrum similar to the one emitted from the DT reaction. However, the value is lower than the one reported in [10] ($\Gamma_1/\Gamma_0 = 2.1 \pm 0.4$) in a recent DT inertial confinement experiment and the two measurements agree only within two standard deviations. Considering that in both works the analysis performed on the χ^2 distribution has assessed the statistical robustness of the measured values, the discrepancy might be caused by systematic uncertainties. For instance, the limited knowledge of the γ ray background caused by DT neutrons could lead to an overestimation of the contribution due to γ_1 which, in the past, has often been not observed, as it was overwhelmed by the background, such as in Refs. [7] and [3]. In this context, we observe that the spectroscopic technique is only available on a continuous source, such as in magnetic confinement fusion or beam-on-target experiments where detection of individual gamma rays is achievable in the so-called pulsed mode operation. In inertial fusion experiments only energy integrated spectra above fixed thresholds are available and the assessment of signal and background levels can be challenging.

The knowledge of the ^{5}He γ ray spectrum is important for the use of the gamma rays to measure the DT fusion power in a tokamak, which is based on the absolute measurement of the total γ_0 and γ_1 emission. In this context, it is important to point out that a variation of the Γ_1/Γ_0 ratio in the range (0.9–1.3):1 introduces an uncertainty in the total gamma ray counts in the region of interest (10 and 20 MeV) of the order of 16 %.

TABLE I. Values in literature of Γ_1/Γ_0 measured for the reactions D^{3}He and DT.

Reference	Reaction	Γ_1/Γ_0	E $_{\text{c.m.}}$ [keV]
Buss *et al.* [6]	D^{3}He	1.0 $\pm$ 0.15	288
Cecil *et al.* [5]	D^{3}He	1.8 $\pm$ 0.8	20-60
[a]Cecil *et al.* [5]	D^{3}He	1.4	20-60
Horsfield *et al.* [10]	DT	2.1 $\pm$ 0.4	∼10

[a]Data from [4] have been reanalyzed with a different model in Ref. [10], but no uncertainties are reported.

IV. CONCLUSIONS

In this work the γ ray spectrum from the ^{3}H(^{2}H, γ)^{5}He reaction has been measured with a large LaBr$_3$ spectrometer installed on a dedicated line of sight at the Joint European Torus. The detector response function and the entire line of sight was simulated with MCNP6 to precisely describe the experimental conditions. This includes the attenuation of the materials between the detector and the plasma as well as the detector response and efficiency. The γ ray lines shapes were calculated following the *R*-matrix formalism of ^{5}He and, after the convolution with detector response function, they have been used to model the measured pulse height spectrum.

The analysis performed has confirmed the presence of a second γ ray line, γ_1, at ≈14 MeV as predicted by the *R*-matrix theory, beside the known main γ_0 ray emission at 16.7 MeV. This has allowed to experimentally assess for the first time in a magnetic confinement experiment the relative yield Γ_1/Γ_0 of γ_0 and γ_1 lines equal to 1.09 ± 0.25.

A better estimation of the relative yield of the two γ rays could be done at pulsed deuterium accelerators on a tritiated target, where the pulsed nature of the source would help to the discrimination between neutrons and γ rays via the time-of-flight technique. However, the needed requirements, namely short-pulse (<100 ns), low deuterium energy (<1 MeV) and long flight-path (>10 m) of the source, to allow for γ ray spectroscopic measurements with discrimination of the neutron background, are not common at accelerator facilities.

The knowledge of the γ ray spectrum of ^{5}He* provided by this work paves the way to the evaluation of the γ to 14 MeV neutron branching ratio (Γ_γ/Γ_n) of the reaction ^{3}H(^{2}H, γ) ^{5}He [24]. A good knowledge of Γ_γ/Γ_n is in fact key for measuring the DT fusion power in a reactor with an alternative method based on absolute γ ray measurement, which would in principle not require the long and time consuming calibrations required for 14 MeV neutron counting [25]. This is relevant for the next generation fusion reactors, such as ITER and DEMO [26], where a second independent measurement of the fusion power is considered mandatory for licensing, safety, and reliable operation.

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