γ-ray emission in proton-induced nuclear reactions on \(^{nat}C\) and Mylar targets over the incident energy range, \(E_p = 30 – 200\) MeV. Astrophysical implications

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Abstract

We have measured the γ-ray line production cross sections in proton-induced nuclear reactions on various target nuclei (\(^{12}\)C, \(^{16}\)O, \(^{24}\)Mg, \(^{28}\)Si, \(^{56}\)Fe) of chemical elements abundant in astrophysical sites (solar flares, the interstellar medium, cosmic compact objects) over the incident energy range of \(E_p = 30 – 200\) MeV. We carried out experimental campaigns in joint collaboration at the \(K = 200\) separated sector cyclotron of iThemba LABS using a high-energy resolution, high-efficiency detection array composed of 8 Compton-suppressed clover detectors comprising 32 HP-Ge crystals for recording the γ-ray energy spectra. In the current paper, we focus on γ-ray de-excitation lines produced in proton irradiations of \(^{nat}C\) and Mylar targets, in particular, on the prominent 4.439 and 6.129 MeV lines of \(^{12}\)C and \(^{16}\)O which are among the strongest lines emitted in solar flares and in interactions of low-energy cosmic rays (LECRs) with the gas and dust of the inner galaxy. We report new γ-ray production experimental cross section data for ten nuclear γ-ray lines that we compare to previous low-energy data sets from the literature, to the predictions of the TALYS code of nuclear reactions and to a semi-empirical compilation. In the first approach, performing calculations with default input parameters of TALYS we observed substantial deviations between the predicted cross sections and experimental data. Then, using modified optical model potential (OMP) and nuclear level deformation parameters as input data we generated theoretical excitation functions for the above two main lines fully consistent with experimental data. In contrast, the experimental data sets for the other eight analyzed lines from the two proton-irradiated targets exhibit significant deviations with the predicted cross section values. We also report line-shape experimental data for the line complex observed at \(E_\gamma = 4.44\) MeV in irradiations of the two targets. Finally, we emphasize the astrophysical implications of our results.

Keywords: Nuclear reactions, Gamma-ray spectrometry, Gamma-ray line shape analysis, Gamma-ray production cross section, Solar flares, Interstellar medium.

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1. Introduction

The last few decades have seen the achievement of considerable progress in the elucidation of the non-thermal acceleration of charged particles in magnetized astrophysical sites, their interactions and transport, as well as the induced radiation processes that provide crucial information on the properties of the energetic particles themselves and of the accelerating media [1, 2, 3, 4, 5]. In this context, the emission of nuclear γ-ray lines produced in violent collisions between highly accelerated ions and abundant nuclei in solar flares (SFs) and the interstellar medium (ISM) has been extensively studied via several complementary methods [6, 7, 8, 10] (and Refs therein). These studies included laboratory measurements of γ-ray cross sections, their comparisons to the predictions of nuclear reaction codes like EMPIRE2 [11] and TALYS [12], the modeling of γ-ray fluxes from astrophysical sites [13, 14, 15, 16] and their comparison to observational data reported by space telescopes such as SMM [17, 18], CGRO [18], RHESSI [19], INTEGRAL [20, 21] or FERMI [22]. This allowed an increasing understanding with time of the nuclear collision processes at work in SFs and the ISM.

In both astrophysical sites, the most important nuclear reactions are those induced by energetic protons and α-particles on the nuclei of abundant chemical elements (H, He, C, N, O, Ne, Mg, Al, Si, S, Ca and Fe), and the inverse reactions between accelerated ions of the latter species and ambient hydrogen and helium [6, 7, 8, 10]. γ-ray lines are from various processes like the de-excitation of directly excited nuclei via inelastic scattering, the products of nuclear reactions (transfer, fusion-evaporation or spallation reactions) and synthesized radioactive nuclei. These reactions give rise, respectively, to a narrow and a broad component of strong lines in the observed complex γ-ray emission spectra from the SFs and ISM, in addition to a non-resolved component of weak lines from highly excited states forming a quasi-continuum [23]. Consequently, the knowledge of γ-ray production cross sections over wide particle energy regimes, as present in solar flares and cosmic rays, extending from reaction thresholds up to hundreds of MeV/u is required.

In a pioneer reference work, Ramaty et al. [6] established in 1979 a database of γ-ray line production cross sections reporting γ-ray experimental cross section data for main de-excitation lines from low-lying excited states produced in nuclear reactions induced by light ions (protons, 3He+ ions and α-particles) on target nuclei from 4He to 56Fe abundant in astrophysical sites. Successively updated in 2002 by Kozlovsky et al. [7] and in 2009 by Murphy et al. [8], this compilation provides extrapolations of existing cross section data to higher projectile energies not covered by experiment. It also predicts the variation trends of γ-ray excitation functions for numerous weak lines emitted by high-lying excited states, exclusively based on TALYS code [12] calculations.

Laboratory measurements of these observables have been carried out mainly at the Washington [24, 25, 26, 27] and Orsay [28, 29, 30, 31, 32] tandem accelerators for reactions induced on various target nuclei by protons and α-particles with incident energies covering the ranges reaching up to $E_p = 26$ and $E_\alpha = 40$ MeV, respectively. Experimental data sets for some γ-ray lines have also been measured at cyclotron facilities for incident energies extending up to $E_p = 50$ MeV and $E_\alpha = 40$ MeV [33] (and references therein). More recently, new data sets for the strongest γ-ray lines produced in α-particle-induced reactions on C, Mg, Si and Fe targets, extending the available data over the energy range, $E_\alpha = 50 - 90$ MeV, have been measured by Kiener et al. [34] at the center for proton therapy of the Helmholtz-Zentrum in Berlin.

The 4439 and 6129 keV transitions from the $J^\pi = 2^+$ first excited state of $^{12}$C and the $3^-$ second excited state of $^{16}$O to the ground states of these nuclei are among the most intense lines in the γ-ray energy spectra from proton-induced reactions [8]. Other intense lines from these reactions [8] are the 511 keV line from the positron-electron annihilation and the 847 keV, 1369 keV, 1634 and 1779 keV lines of $^{56}$Fe, $^{24}$Mg, $^{20}$Ne and $^{28}$Si, respectively, and the 2223-keV line from neutron capture on hydrogen, which is a very prominent line in solar flares.

The 4439 and 6129 keV lines are produced in astrophysical sites mainly via inelastic proton and α-particle scatterings of $^{12}$C and $^{16}$O nuclei, respectively, and (for the 4439 MeV line) in the $^{16}$O(p, $p\alpha$)$^{12}$C and $^{16}$O($\alpha$, 2$\alpha$)$^{12}$C reactions and in interactions of accelerated $^{12}$C and $^{16}$O ions with abundant hydrogen and helium. Production cross sections for these two lines are available up to $E_p = 85$ MeV [35], and $E_\alpha = 90$ MeV for the 4439 keV line of $^{12}$C [34]. However, experimental γ-ray production cross-section data yet remains lacking for higher proton energies. These two transitions are of great importance for line shape studies in particle-induced nuclear reactions, as pointed out by Kiener [30] who has recently performed a detailed and comprehensive line shape analysis on the 4439-keV γ-ray transition in $^{12}$C in terms of dominant nuclear reaction mechanisms. Indeed, the γ-ray line shape analysis could allow extracting important information on the properties of the accelerated particle populations, the underlying particle acceleration mechanism and the magneto-hydrodynamic structure of these sites [37, 38].

We have measured γ-ray line production cross sections for 30-200 MeV protons accelerated on various target nuclei of astrophysical concern at the separated sector cyclotron (SSC) of iThemba LABS (near Cape Town, in
South Africa). We have reported part of the experimental data sets involving the Si, Mg and Fe targets in a recent publication [10]. This work extended previous experimental data for the main lines of these nuclei to higher proton energies up to $E_p = 66$ MeV and allowed us to obtain cross section data for some weaker lines.

In the present paper, we report new experimental data for de-excitation $\gamma$-ray lines produced in proton-induced nuclear reactions on $nat$C and Mylar targets over the incident energy range of $E_p = 30 - 200$ MeV. In section 2 we provide experimental details on the set-up and procedure used. We present our data analysis and experimental results in section 3. In section 4 we compare the extracted $\gamma$-ray line production cross sections to previous data sets from the literature. Then, we compare them in section 5 to values predicted by nuclear reaction models derived via TALYS code [12] calculations and by the compilation of Murphy, Kozlosky, Kiener and Share [8]. Finally, a summary and perspectives are given in section 6 where we also emphasize the astrophysical implications of our results.

2. Experiments

One can find a detailed description of the set up and methods used in our recent paper [10].

Since previous experimental $\gamma$-ray line production cross section data sets were available mostly for proton energies extending up to $E_p = 26$ MeV [8, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34], we decided to investigate the higher proton energy region of $E_p = 30 - 200$ MeV, allowed by the SSC facility of iThemba LABS. We have thus undertaken experimental campaigns in joint scientific collaboration, taking data over the energy regions of $E_p = 30 - 66$ MeV, $66 - 125$ MeV and $125 - 200$ MeV in 2014 - 2016. More precisely we carried out measurements at proton beam energies of $E_p = 30, 42, 54$ and 66 MeV in 2014, $E_p = 66, 80, 95, 110$ and 125 MeV in 2015, and $E_p = 66, 125, 150, 175, 200$ MeV in 2016. That is a total of 11 different beam energies, (the measurements at $E_p = 66$ and 125 MeV being repeated for data checking). Proton beams were delivered by the cyclotron accelerator with current intensities in the range of $I = 2 - 5$ nA, and focused onto $nat$C, Mylar (chemical composition $C_{10}H_{24}O_4$) and other (Mg, Al, Si, Ca and Fe) targets of interest. A well-manufactured, electrically isolated Faraday cup placed 3 m downstream of the reaction chamber (protected deep inside a thick concrete wall) served to stop the incident proton beam and to measure its integrated current with high precision of $\approx 1\%$. The collected total beam charge was typically of $\approx 5 \mu C$ for a run of 1-hour duration. In all our experiments, we used self-supporting, natural or isotopically enriched solid targets that were prepared at iThemba LABS (Cape Town) and we brought some of them from the CSNSM-Orsay. Table 1 reports the properties of the $nat$C and Mylar targets that had thicknesses of 8.4 and 7 mg cm$^{-2}$, respectively, while the other elemental targets had thicknesses in the range of 6 - 9.8 mg cm$^{-2}$ (see Ref. [10]). The targets were mounted on rectangular Al frames, then onto a common holder. An Al frame without target and a fluorescent Al$_2$O$_3$ beam viewer with a central 3 mm diameter hole devoted, respectively, to measuring the beam-induced $\gamma$-ray background and for beam tunings. The AFRODITE detection array mounted in a rhombicuboctahedron frame [35, 36, 41] served to us for detecting the nuclear $\gamma$-rays. It consisted of eight clover detectors of the EUROGAM phase II type [12] each containing four 50 x 70 mm HP-Ge crystals of n-type, housed in a common cryostat and Compton-suppressed by means of BGO crystals. In the configuration of fixed geometry used, four clovers were set at $\theta_{lab} = 90^\circ$ and the other four backward at 135$^\circ$ with respect to the incident proton beam direction. Fig. 1 reports a schematic diagram of the experimental set up illustrating the passage of the proton beam across the AFRODITE reaction chamber equipped with the associated $\gamma$-ray clover detection array in the configuration used in our experiments. An average distance of $\approx 19.6$ cm separated the front face of each HP-Ge crystal from the studied target. Then, the whole detection system subtended a solid angle amounting to a substantial fraction of $\approx 7.5\%$ of the total $4\pi$sr. The individual HP-Ge crystals within a clover were set symmetrically at angles $\pm 5$ degrees relative to its center. This configuration of 32 HP-Ge crystals thus allowed us to measure $\gamma$-ray angular distributions with four detection angles each, i.e., $\theta_{lab} = 85^\circ, 95^\circ, 130^\circ$ and $140^\circ$. In the 2016 experimental campaign we extended this limited angular range by placing one of the clovers at $169^\circ$, thus its HP-Ge crystals were positioned at $\theta_{lab} = 166^\circ$ and $172^\circ$ (it had no BGO-Compton background suppression). This configuration of the AFRODITE $\gamma$-ray detection array actually allows for placing clovers at a forward angle relative to the incident beam direction, namely at $\theta_{lab} = 45^\circ$. However, given that the angular distributions of the $\gamma$-ray emission are expected to be symmetric relative to $90^\circ$ we voluntarily avoided this option as precaution for protecting the HP-Ge crystals against risky damages under high fluxes of neutrons produced in multi-scattering and reactions of the proton beam with the surrounding material elements (mainly Al and Ge) and the studied targets themselves. Both preceding TALYS code calculations and an experimental test run using a neutron detector performed prior to these experiments have pointed out the occurrence of important neutron backgrounds from these processes, especially at forward angles. The iron target was found to be the most critical one regarding neutron production via the $^{56}$Fe ($p, x n$) reaction. The corresponding $\sigma_n$ total production section section is proton energy-dependent. E. g., at $E_p = 66$ MeV, we
obtained a value of $\sim$1 b for this cross section that remains nearly constant over the proton energy range of $E_p = 50$ - 80 MeV, while lower values of $\sigma_n \sim 150$, 200 and 250 mb were derived in case of the $^{12}$C, $^{24}$Mg and $^{28}$Si targets, respectively. Over the higher proton beam energy range of $E_p = 80$ - 140 MeV, our Talys code calculations yielded a value of $\sim$350 mb for $\sigma_n$ around the characteristic neutron peak at energy $E_n = 1.0$ MeV, then $\sigma_n$ (which varies as $1/E_n$) decreased to $< 5$ mb for higher neutron energies. Further details are provided on this point later in Subsection 3.2.

We expected the observation of nuclear $\gamma$-ray lines of interest with energies extending up to about 7.2 MeV including the de-excitation lines at $E_\gamma = 6.129$, 6.916 and 7.115 MeV from the $3^-$, $2^+$ and $1^-$ low-lying states of $^{16}$O. We performed a careful energy calibration of the $\gamma$-ray detection array using standard radioactive sources of $^{60}$Co, $^{137}$Cs and $^{152}$Eu. The latter were placed at target position in the reaction chamber, and thus allowed us to cover the low photon energy range of $E_\gamma = 0.122$ – 1.408 MeV. Sometimes, we also used a locally produced $^{56}$Co source for extending the $\gamma$-ray energy range up to $E_\gamma \approx 3$ MeV. In addition, the prominent 6.129 MeV line of $^{16}$O and its escape lines produced in the (p, $p'_\gamma$) inelastic scattering off the Mylar target were used for photon energy calibration. The energy resolution, frequently checked with respect to the 1.332 MeV line from the $^{60}$Co radioactive source, amounted typically to 2.5 keV. We have used the same standard radioactive sources of $^{60}$Co, $^{137}$Cs and $^{152}$Eu for measuring the absolute efficiencies of the detection system over the low photon energy range up to $E_\gamma = 1.408$ MeV. Then, we extrapolated the obtained values to higher photon energies, up to $E_\gamma \approx 10$ MeV, via performing detailed Monte Carlo simulations of the AFRODITE detection array and surrounding material using the GEANT4 software.

In each performed experimental run with the proton beam-on target under high vacuum, we recorded $\gamma$-ray energy spectra from the nuclear reactions of interest until the collection of good counting statistics in the less intense $\gamma$-ray peaks was obtained. We systematically recorded $\gamma$-ray background energy spectra from various related sources, such as experimental room, beam-induced, target and surrounding material activation backgrounds. Then, we used the accumulated background data for correcting the counts in the energy spectra of interest and as insights for possible spurious events in the latter. In particular, we subtracted the beam-induced backgrounds recorded with the incident protons passing through the Al empty-target frame from the measured main $\gamma$-ray energy spectra, upon normalizations to the same accumulated proton beam charges. Throughout all the experimental runs, we took great care for protecting the HP-Ge crystals via limiting their possible deterioration under the impact of excessive neutron backgrounds. The count rates in the detectors were not exceeding 5 - 6 kHz per crystal, and were lower than 0.5 kHz during the runs with beam on the empty-target frame. All the experimental runs were in general operated with proton beam current intensities of at most 5-6 nA and counting dead times of 6 - 8% (see also Ref. 10).

During the experiments, we used a data acquisition system (the Multi Instance Data Acquisition System, MIDAS, [43]) based on digital electronics modules made by XIA of type “DGF Pixie-16”.

We worked the experimental runs generally in favorable, stable operating conditions, constantly monitoring the data acquisition system and the $\gamma$-ray count rates, and checking the levels of the neutron and $\gamma$-ray backgrounds in the recorded spectra. When unwanted variations occurred in the beforehand fixed conditions, we proceeded to additional tunings of the proton beam settings. We systematically saved the recorded $\gamma$-ray energy spectra on discs together with timing and energy information.

3. Data analysis, experimental results

After the experiments, the count rate contents of the measured raw experimental data sets ($\gamma$-ray line energy and efficiency calibrations of the AFRODITE detection array, energy spectra and angular distribution data) have been checked and further corrected for dead time losses. Then, the data sets were analyzed using well-adapted homemade methods or software toolkits available in the literature as described below in this Section. In particular, the $\gamma$-ray line peaks within the energy spectra were accurately identified with evaluating the spurious background lines, the relevant $\gamma$-ray line transitions were determined with carefully identifying the involved de-excitation nuclear states. Then, a line-shape analysis was performed with applying a special treatment in order to extract the components contributed by different isotopes in observed, Doppler-broadened $\gamma$-ray line structures of complex shapes growing around $E_\gamma = 4.44$ MeV within the energy spectra from both two studied $^{12}$C and Mylar targets.

Below, we first start with presenting a precise evaluation of the AFRODITE detection array absolute efficiencies using simultaneously experimental data from the $^{137}$Cs, $^{60}$Co and $^{152}$Eu calibrated radioactive sources up to $E_\gamma = 1.408$ MeV and Monte-Carlo GEANT4-simulated values over the photon energy range of 0.08 – 10 MeV, thus extending the measured data up to $E_\gamma = 10$ MeV. Finally, upon elaborated angular distribution Legendre polynomial least squares fits to the $\gamma$-ray differential experimental cross section data, we determine the corresponding angle-
integrated γ-ray line production cross sections. Detailed accounts of the uncertainties affecting each of the above quantities are provided below in this section.

3.1. γ-ray detection efficiencies

As indicated in the previous section, we have evaluated the absolute γ-ray detection efficiency, $\varepsilon(E_{\gamma}, \theta)$, for a large photon energy domain of interest. Experimental values taken with the calibrated radioactive sources covered the energy range of $E_{\gamma} = 122 - 1408$ keV. They were determined using the relation

$$\varepsilon(E_{\gamma}) = \frac{N_{\gamma}(E_{\gamma})}{A(t) \times \Delta t \times I},$$

in terms of the γ-ray line count integrals (photo-peak areas) in the γ-ray energy spectra, $N_{\gamma}(E_{\gamma})$, the radioactive source activities at the measurement time, $A(t)$, the acquisition time interval, $\Delta t$, and the nuclear γ-ray branching ratios, $I$.

The uncertainty in the detection efficiencies obtained with the radioactive sources is dominated by the uncertainty in the source activity amounting to 3.7 – 5%, while the branching ratios contribute by less than 1% and the statistical error in the peak areas amounts to 1-2%.

We extended the γ-ray energy range up to 3.5 MeV by using efficiency data from a previous experiment carried out with an uncalibrated $^{58}$Co source under identical conditions as in the present work, normalized to our experimental data. The systematic uncertainty in this normalization was found to be of less than 2% based on the deviation in the region of overlap between the data sets.

Extrapolation of the $\varepsilon(E_{\gamma}, \theta)$ data to higher photon energies was based on Monte-Carlo simulations. Indeed, simulating the γ-ray emission from the radioactive sources using the GEANT4 program, we first reproduced the corresponding experimental spectra as shown in Fig. 2. Then, simulated efficiency values were determined for each HP-Ge crystal, allowing us to extend the data from the sources to higher γ-ray energies. Gamma-ray line sum peaks following true coincidence-cascades between full-absorption energy γ-rays from the sources, expected to grow in the experimental spectra, were found to be of very low intensities amounting to less than 0.05% relative to the intensities of the latter photo-peak lines. Consequently, they should not have appreciable effects on the absolute detection efficiency data.

While the GEANT4 simulations tend to overestimate the absolute efficiency, it had been shown that they reproduce the energy dependence of the HP-Ge detection efficiencies accurately, with no adjustable parameters. The GEANT4 simulations were performed at source energies and at regular energy intervals between 80 keV and 10 MeV. They were normalized to the efficiencies obtained with the radioactive sources over the photon energy range of $E_{\gamma} = 0.5 - 1.4$ MeV, the scaling factors between the two data sets amounting to 0.87, in average.

We then derived the values of $\varepsilon(E_{\gamma}, \theta)$ for each detector and versus the photon energy via interpolating all the data using the following multi-parameter function reported in the RadWare software package, i.e.,

$$\varepsilon(E_{\gamma}, \theta) = e^{[X + (A + BX + CX^2 - G + (D + EY + FY^2 - G)^{-G})^{-1/G}]/100}$$

where $X = \log(E_{\gamma}/100)$, $Y = \log(E_{\gamma}/1000)$ and the other quantities are adjustable free parameters.

The fitted curves were used for deriving the absolute detection efficiency values for each observation angle and versus the photon energy, and subsequently for calculating the γ-ray cross sections.

Fig. 3 shows the measured efficiencies, the normalized GEANT4 simulated values and the fitted curve to these data points (solid line). The dotted lines in this figure indicate an average uncertainty of the order of 12% estimated here for the overall absolute efficiencies of the AFRODITE detection array. For this purpose, we mainly took into account the statistical errors resulting from the calculation of the photopeak areas within the γ-ray energy spectra, to which we added in quadrature the uncertainties in the radioactive source activities, in the γ-ray branching ratios, in the GEANT4-simulated values, in the normalization factors and in the fits of the multi-parameter function to the data.

The values of the absolute efficiencies at high energies are further supported by the obtained good agreement between our experimental cross sections reported here for the lines at $E_{\gamma} = 4.44$ and 6.129-MeV of $^{12}$C and $^{16}$O, respectively, and the previously measured values (available for beam energies below 50 MeV).

3.2. γ-ray energy spectra, transitions properties

One can use two operating modes for treating the raw experimental data (γ-ray count rates, energy spectra, detection efficiencies, etc.) from a given clover, either the single HP-Ge crystal mode or the add-back mode consisting in summing the energies detected in two adjacent crystals of the clover. In this work we used the former mode.
in the data analysis given that the counting statistics from each HP-Ge crystal was sufficient, thus, we considered each Ge crystal as an individual Compton background-suppressed detector. To improve the Compton background suppression we also rejected coincident events between elements of a clover detector. Along this phase, we often checked the consistency of the estimated experimental values of γ-ray cross sections with corresponding orders of magnitude predicted by nuclear reaction models using the TALYS code.

After the experiments, we continued the treatment and analysis of the recorded experimental data in order to extract as accurately as possible γ-ray angular distribution and production cross section data. We analyzed the γ-ray peaks within the photon energy spectra following the method detailed in Refs. [10, 23, 29] by means of the ROOT software [40] or the gFlash software [41]. We extracted their areas by fitting symmetric Gaussian-shaped distributions to the measured data with subtracting the related backgrounds by linear function fits. However, Gaussian shape fits to the experimental data were not always applicable, and a special method was used to extract the γ-ray line areas as, for instance, for the line of $^{12}$C at $E_γ = 4.439$ MeV (see the next subsection). We evaluated the total relative uncertainty of each peak area as the sum in quadrature of the uncertainty resulting from the fitting procedure, the statistical uncertainty and the systematic uncertainty. The latter two uncertainties amounted to at most 5 and 10%, respectively. As described in the previous section, we performed precise determinations of the γ-ray line energies within the recorded spectra with absolute uncertainties typically amounting to less than 0.1 keV. Fig. 4 reports examples of experimental energy spectra in single mode from two individual HP-Ge detectors located, respectively, at observation angles, $θ_{lab} = 130^°$ and $85^°$: (a) for a 54 MeV proton beam incident on the natC target and (b) in case of a 150 MeV beam hitting the Mylar foil. One can notice great similarities in the general shapes (γ-ray lines + backgrounds) of these γ-ray energy spectra with presence of the intense background line at 511 keV from the positron-electron pair annihilation, as well as marked differences featuring their contents in γ-ray line peaks due to the differences in their respective target compositions. Fig. 4 also illustrates that while the Compton background was reduced by the BGO suppression, it was not fully removed. Figs. 5 and 6 report separately the γ-ray energy spectra from the same two HP-Ge detectors, corrected for proton beam-induced backgrounds, after further subtracting the Compton background and the background from the reaction chamber in the subsequent data analysis phase.

The recorded γ-ray energy spectra thus exhibit several γ-ray lines of various shapes and intensities, the most intense, narrow peak of interest corresponds to the line of $^{10}$B at $E_γ = 0.718$ MeV (see Figs. 5 and 6). Some of the observed lines, like the lines of $^{11}$C and $^{12}$C at $E_γ = 2.000$ and 4.439 MeV, respectively, are subject to strong Doppler broadening and shift making their analysis rather difficult, as will be clarified in next subsection. We pointed out 20 peaks corresponding to de-excitation lines from various isotopes produced in proton-induced reactions. Notably, the lines at $E_γ = 4.439$ and 6.129 MeV referring to the E2 ($2^+, 4.439$ MeV, $τ = 42$ fs $→ 0^+, g.s$) and E3 ($3^−$, 6.129 MeV, $τ = 18.4$ ps $→ 0^+, g.s$) transitions in $^{12}$C and $^{16}$O, respectively, produced in (p, p’γ) inelastic proton scattering, suffer considerable Doppler broadenings ($≈ 150$ keV for the 6.129 MeV line), which makes them good candidates for line shape analyses [32]. Tables 2, 3 display separately the lists and properties of the identified γ-ray transitions resulting from proton-beam-induced reactions on the natC and Mylar target, respectively. They correspond to the de-excitation of various low-mass isotopes ($^{10}$B, $^{11}$, $^{12}$, $^{13}$C, $^{14}$N, $^{15}$N, $^{15}$O) produced in (p, p’γ) inelastic proton scattering, fusion-evaporation reactions and spallation reactions induced by high-energy protons on $^{12}$C and $^{16}$O (see Tables 2, 3). As can be seen in these tables, the (Eγ, θ) line transitions pointed out have essentially M1, E2, E3, (M1 + E2), (M2 + E3) and (E1 + M2 + E3) characters with multipolarity values not exceeding $λ = 3$. In addition, the energy spectra show the presence of background peaks for γ-ray lines emitted in proton and secondary neutron-induced reactions on the nuclei of surrounding Al and Ge elements from the reaction chamber, the target frames and holder, and the HP-Ge detectors [47, 48]. In particular, several γ-ray lines with asymmetric shapes appear in the energy spectra. They refer to background de-excitation lines produced in inelastic secondary neutron scattering off Ge isotopes. These are emission lines at $E_γ = 198$ keV coming from the $^{70}$Ge(n, $γ$)$^{71}$Ge radiative neutron capture reaction, $E_γ = 595.85$ keV from the (n, n’γ) inelastic neutron scattering of $^{74}$Ge, and $E_γ = 689.60$, 834.01 and 894 keV from the (n, n’γ) inelastic neutron scattering of $^{72}$Ge. In addition to the 511 keV line, the energy spectra contained background lines from $^{27}$Al, like the lines at $E_γ = 843.76$ keV resulting from both the $^{27}$Al(n, p) $^{27}$Mg*(β−)$^{27}$Al sequential process and the (p, p’γ) inelastic proton scattering of $^{27}$Al, 1.014 MeV from the latter reaction and 1.369 MeV from the $^{27}$Al(p, αγ)$^{24}$Mg reaction, etc. Notice that apart from the 198 keV background line, no γ-ray lines of interest dominated the low-energy part of the γ-ray energy spectra below the positron-electron annihilation line at $E_γ = 511$ keV. Table 4 lists most of the observed background lines, together with the corresponding nuclear reactions. The background lines practically affected all the γ-ray energy spectra recorded in our experiments involving the proton beams (see, e.g., Figs. 4 (a, b)).
3.3. γ-ray line shape data, analysis of the 4.44 MeV line complexes

As one can see in Figs. 3(a, b), a broad structure appears at $E_\gamma \sim 3.3 - 4.5$ MeV in the γ-ray energy spectra from both natural C and Mylar targets. These are actually line complexes composed of overlapping, Doppler-broadened lines of interest, together with their Compton components and escape peaks. In the case of the C target, in addition to the 4.439-MeV line, which is the dominant line, two other γ-ray lines at $E_\gamma = 4.319$ and $4.444$ MeV attributed to $^{11}\text{C}$ and $^{11}\text{B}$, respectively, are significant components of the complex (see Fig. 5 Table 3). Nuclear reaction code calculations predict that the 4.439 MeV line of $^{12}\text{C}$ is the only component below $E_p = 25$ MeV, while above this energy the 4.445 MeV line of $^{11}\text{B}$ significantly contributes via the $^{12}\text{C}(p, 2p)^{11}\text{B}$ reaction, as well as the 4.319 MeV line of $^{11}\text{C}$ via the $^{12}\text{C}(p, \alpha)^{11}\text{C}$ reaction. Some minor components like the 4.339 MeV line of $^{11}\text{C}$ and the 4.444 MeV line of $^{10}\text{B}$ are probably also present.

In such conditions, the determination of the full-energy peak contents requires a special treatment. Therefore, we were led to perform meticulous spectral deconvolution concerning the peak associated with the line of $^{11}\text{C}$ at $E_\gamma = 4.319$ MeV appearing on the left side of the line complex at $E_\gamma = 4.44$ MeV. To this end, we generated the corresponding theoretical spectral shape as follows. We subtracted the Compton background and escape peaks by means of the γ-ray energy-deposit spectra in the HP-Ge crystals that were simulated by the GEANT4 program over an extended photon energy domain, $0.5 \leq E_\gamma \leq 7$ MeV. The response functions of the HP-Ge detectors also required careful checking via simulations of the γ-ray emission spectra, which one could do for standard radioactive sources of known branching ratios placed at the target position and then compare the simulated and experimental spectra. This is illustrated in Fig. 3 (discussed in Subsection 3.1.) reporting an example of experimental spectra from calibrated $^{152}\text{Eu}$ and $^{60}\text{Co}$ radioactive sources recorded with an HP-Ge detector in the 2016 experimental campaign together with their GEANT4-simulated counterparts. The observed very good agreement in this figure between the experimental and simulated energy spectra then attests for the correctness of the operating methods used in the current work.

We derived the contribution of the 4.319 MeV line of $^{11}\text{C}$ after calculation of its line shape following the method described in Ref. 41. For this purpose, we used a simulation program of Monte-Carlo type written by Kiener 50 with taking into account the geometry and the energy resolution of the HP-Ge detector. We used as input data for the $^{12}\text{C}(p, p\alpha)^{11}\text{C}$ reaction in this program the angular distributions for particle emission and the mean excitation energy of the nuclear state derived by TALYS code calculations. We assumed the slowing down within the target of the $^{11}\text{C}$ isotope in its excited state ($\tau < 8.3$ fs) to occur with exponentially decreasing γ-ray emission probability, evaluating the target stopping power by the SRIM code 51.

Fig. 7 reports the obtained results for the simulated spectra for the $^{11}\text{C}$ line at $E_\gamma = 4.319$ MeV, while Fig. 8 illustrates the evolution versus the proton beam energy and observation angle of the line shape data in the complex at $E_\gamma = 4.44$ MeV after subtraction of the simulated spectra for the line of $^{11}\text{C}$. Obviously, the separation of the Doppler-broadened peaks at $E_\gamma = 4.349$ and $4.444$ MeV for the lines of $^{12}\text{C}$ and $^{11}\text{B}$, respectively, is impossible. We therefore attributed the counts remaining after the subtraction of the 4319-keV line to a line labelled 4.44-MeV, which is the sum of the 4439-keV, 4444-keV and some minor lines as discussed above.

The interaction of the proton beam with the Mylar ($^{12}\text{C}_{10}\text{H}_{8}\text{O}_{4}$) target produces nuclear reactions simultaneously with $^{12}\text{C}$ and $^{16}\text{O}$, which leads to the superposition of de-excitation γ-ray lines from these two target nuclei. In this case also, the extraction of the areas under the peaks for the line of $^{12}\text{C}$ at $E_\gamma = 4.439$ MeV produced in the $^{16}\text{O}(p, p\alpha)^{12}\text{C}$ reaction required a special treatment.

After subtraction of the Compton backgrounds and the 4.319 MeV line components ($N_{\gamma}^{\text{tot}}$), the target thicknesses ($N_t$), and the 4.319 MeV line of $^{11}\text{C}$ similarly as explained above, the 4.44 MeV complex in each γ-ray energy spectrum contained four components. Two components for the 4.439 line of $^{12}\text{C}$ resulting from the $^{12}\text{C}(p, p\alpha)^{12}\text{C}$ and $^{16}\text{O}(p, p\alpha)^{12}\text{C}$ reactions, respectively, and the two components for the line of $^{11}\text{B}$ at $E_\gamma = 4.444$ MeV from reactions with $^{12}\text{C}$ and $^{16}\text{O}$. In the spectra from this target (Mylar), the count integrals ($N_{\gamma}^\text{tot}$) are sums of the integrals ($N_{\gamma}$) from the two preceding reactions, respectively.

We subtracted the 4.439 MeV and 4.444 MeV line components ($N_{\gamma}$) due to reactions with $^{12}\text{C}$ with the help of the energy spectra recorded in proton irradiations of the natural C target (γ-ray line integrals, $N_{\gamma}^\text{t}$), following the respective accumulated beam charges in the runs with the C and Mylar targets and the respective numbers of C atoms in each target.

As in the preceding case (lines in the spectra from the natural C target), the two components at 4.439 MeV and 4.444 MeV (from $^{12}\text{C}$ and $^{11}\text{B}$, respectively) of the line complex in each energy spectrum from the $^{16}\text{O}$ isotope in the Mylar target are attributed to the 4.44-MeV line.

3.4. γ-ray angular distributions and integral cross sections

3.4.1. Angular distributions

We derived the γ-ray differential experimental cross section data from the extracted γ-ray line count integrals, $N_{\gamma}(E_{\gamma}, \theta)$, the absolute detection efficiencies $\varepsilon(E_{\gamma}, \theta)$, the target thicknesses (number of nuclei per cm$^2$), $N_t$, and
the numbers of projectiles falling on the targets, \( \phi \), (recorded in the experimental runs) using the relation

\[
\frac{d\sigma(E_{\gamma}, \theta)}{d\Omega} = \frac{N_{\gamma}(E_{\gamma}, \theta)\epsilon(E_{\gamma}, \theta)\lambda}{\varepsilon(E_{\gamma}, \theta)N_{I}\phi}\times10^{27}\text{ (mb/sr)}.
\]  

(3)

We then fitted the following angular distribution Legendre polynomial expansion to the measured data, i.e.,

\[
W(\theta) = \sum_{\ell=0}^{\ell_{\text{max}}} a_{\ell}Q_{\ell}P_{\ell}(\cos(\theta)).
\]  

(4)

The summation in this expression extends over only even, integer \( \ell \)-values, with \( \ell_{\text{max}} \) taking twice the \( \gamma \)-ray multipolarity or twice the spin of the emitting state. Since the studied \( \gamma \)-ray lines are featured by at most \( \lambda = 3 \) (see Tables 2 and 3), this then fixes \( \ell_{\text{max}} = 6 \). The \( Q_{\ell} \) are energy-dependent geometrical attenuation coefficients \(^{52, 53}\), functions of \( (\varepsilon, \theta, \ell) \), that were introduced for taking into account the finite dimensions of the \( \gamma \)-ray detectors and for better evaluating the angular distribution expansion. Their precise determination via GEANT4 Monte-Carlo simulations of the AFRODITE detection array yielded roughly constant values equal or close to unity over the photon energy range of interest, \( 0.1 \text{ MeV} \leq E_{\gamma} \leq 10 \text{ MeV} \), with relative uncertainties of \( \sim 1\% \). Notice that since one is dealing with proton-induced reactions on appreciably heavier target nuclei, all the results reported here were derived under the assumption, \( \theta = \theta_{\text{lab}} \approx \theta_{\text{em}} \). We report as examples in Figs. (a, b) the experimental angular distribution data derived versus the proton energy for the main, prominent \( \gamma \)-ray lines of \( ^{12}\text{C} \) and \( ^{16}\text{O} \) at 4.44 and 6.129 MeV, respectively, together with corresponding least-squares Legendre polynomial best-fit curves generated by Eq. (4). Table 5 displays the associated \( a_{\ell} \) fit coefficients. The reduced \( \chi^{2} \) values resulting from the fits amounted to one or below one for the narrow, isolated \( \gamma \)-ray lines, and to at most three in case of overlapping, broad line structures in the energy spectra. We derived the uncertainties in the experimental differential cross sections by adding in quadrature the errors in the quantities used in Eq. (3). An overall average value of \( \sim 17\% \) of the relative uncertainty in these data then resulted.

### 3.4.2. Integral cross sections and associated uncertainties

The angle-integrated \( \gamma \)-ray line production cross sections were determined from the \( a_{0} \) coefficients of the angular distribution expansions given by Eq. (4) using the relation \( \sigma = 4\pi a_{0} \). Among 20 identified \( \gamma \)-ray lines of interest in the recorded energy spectra (9 lines from the \( ^{nat}\text{C} \) target and 11 lines from Mylar, see Tables 2 and 3), only 10 lines (5 lines from each target) were found intense enough to extract integrated cross sections. We report in Figs. (10) and (11) the obtained \( \sigma(E_{\gamma}) \) excitation function results for the analyzed most intense five \( \gamma \)-ray lines observed in the proton irradiations of the \( ^{nat}\text{C} \) target. We also report in Figs. (12) and (13) similar results obtained for the strongest five lines from the proton irradiations of the Mylar target. Finally, we list in Table 6 the determined values of the integrated \( \gamma \)-ray line cross sections for the identified ten most intense \( \gamma \)-ray lines emitted in proton irradiations of the \( ^{nat}\text{C} \) and Mylar targets. Notice that only five experimental data points (from expected 11) are present in the excitation function for the 6.129 MeV octupole \( \gamma \)-ray transition in \( ^{16}\text{O} \). These data points come from the runs of the 2016 experimental campaign performed using the extended detection setup with the HP-Ge detector placed at \( \theta = 169^\circ \).

The error bars in the differential cross sections influence the Legendre polynomial expansion (Eq. 4) fits to the data leading to the values of the \( a_{\ell} \) coefficients and associated errors, in particular for the \( a_{0} \) term enabling the calculation of the integral cross sections and related errors.

We have primarily estimated the errors propagating in Eq (3) that affect the quantities used for calculating the experimental differential cross sections. Statistical errors were first considered alone in the fit procedure, then systematic errors were added in quadrature in order to generate the final values of the uncertainties in the determined \( \sigma(E_{\gamma}) \) data. The systematic uncertainties usually affect equally the measurements at all the observation angles. We have mainly taken into account the errors in the target thicknesses (1%), the errors associated with the absolute detection efficiencies, \( \varepsilon(E_{\gamma}, \theta) \), typically amounting to at most 12%, as discussed in Subsection 3.1, and those in the collected beam charge (1%).

As statistical uncertainties, we considered the errors in the \( \gamma \)-ray line count integrals (line peak areas), \( N_{\gamma}(E_{\gamma}, \theta) \), within the measured \( \gamma \)-ray energy spectra. Typically, these errors do not exceed 5% in case of isolated, narrow \( \gamma \)-ray lines of Gaussian shapes. In contrast, for Doppler-broadened, overlapped lines of non-Gaussian shapes like the line complexes at \( E_{\gamma} = 4.44 \text{ MeV} \) (see Subsection 5.3), the evaluation of statistical errors is much more complicated, yielding much larger values of at least 10-12%.

In summary, adding in quadrature the above two types of uncertainties (systematic and statistical) and the uncertainty in the Legendre polynomial fits, we obtained mean values of 18-25% for the overall relative uncertainty in the \( \sigma(E_{\gamma}) \) data in case of isolated, narrow lines, and values in the range of 20 - 30% in case of Doppler-broadened,
overlapping lines. These uncertainties are also depicted in Figs. (10-13) and listed in Table 6 together with the corresponding values of the integral $\gamma$-ray line production cross sections.

4. Comparison of our $\gamma$-ray production cross sections to previous data sets

One remarks in Figs (10-13) that among the analyzed 10 intense lines from the two targets, previous experimental data sets are mostly available for the two main lines of $^{12}\text{C}$ and $^{16}\text{O}$ at $E_\gamma = 4.439$ and 6.129 MeV, respectively, the former line being produced in proton irradiations of both the $^{nat}\text{C}$ and Mylar targets (see Tables 2, 3). They cover especially the low proton energy region, $E_p \leq 26$ MeV, dominated by the compound resonance structure at $E_p = 20 - 30$ MeV investigated with tandem accelerators by the Orsay [9, 28, 29, 30, 31, 32] and Washington [24, 25, 26, 27] groups, while only a few data points taken with cyclotrons [33, 35] are present at higher proton energies.

4.1. Lines from the $^{nat}\text{C}$ target

We have identified nine lines in proton irradiations of the $^{nat}\text{C}$ target (see Table 2). We extracted the $\sigma(E_p)$ data shown in Figs. (10-11) for the five most intense lines. These are the main, prominent line at $E_\gamma = 4.439$ MeV from inelastic proton scattering of $^{12}\text{C}$ (set at $E_\gamma = 4.44$ MeV as explained in subsection 3.3), and the lines at $E_\gamma = 0.718$ and 1.022 MeV of $^{10}\text{B}$, $E_\gamma = 2.000$ MeV of $^{11}\text{C}$ and $E_\gamma = 2.124$ MeV of $^{11}\text{B}$ produced in various other nuclear reactions (see Table 2). Regarding the 4.439 MeV main line of $^{12}\text{C}$, one can observe in Fig. (10) that our experimental data are in very good agreement with practically all the previous data sets measured at cyclotron facilities by Lesko et al. [33] and Lang et al. [35] over the common proton energy range of $E_p = 30 - 85$ MeV. They also show to be fully consistent with the lower energy data sets taken previously at tandem accelerators below $E_p = 30$ MeV [9, 24, 25, 26, 27, 32, 33].

Experimental data have been measured previously by Lang et al. [32] at three proton energies, $E_p = 40$, 65 and 85 MeV for the lines of $^{11}\text{C}$ and $^{11}\text{B}$ at $E_\gamma = 2.000$ MeV and $E_\gamma = 2.124$ MeV, respectively. As one can see in Fig. (11) their data at $E_p = 40$ MeV agree very well with our data at $E_p = 42$ MeV, while their two other values lie slightly higher relative to our values, mainly for the line of $^{11}\text{B}$ at $E_\gamma = 2.124$ MeV. Finally, concerning the two lines of $^{10}\text{B}$ at $E_\gamma = 0.718$ and 1.022 MeV, no previous experimental values were reported in the literature that could be compared to our data points (see Fig. (11). While a second cross-section maximum around 70 MeV due to fusion-evaporation reactions, predicted by TALYS [12] and the compilation of Murphy et al. [8], has been indeed pointed out in the recent experiments [34] with accelerated $\alpha$-particles on C, Mg, Si and Fe targets, no evidence for similar trend is shown by the present experimental data from proton-induced reactions.

4.2. Lines from the Mylar target

We report in Figs. (12, 13) experimental $\sigma(E_p)$ data for the five most intense lines among eleven lines identified in the proton irradiations of the Mylar target (see Table 3). One can see in Fig. (12) that for the octupole line of $^{16}\text{O}$ at $E_\gamma = 6.129$ MeV only five experimental data points are shown at $E_p = 66$, 125, 150, 175 and 200 MeV out of the 11 proton energies explored in our experiments, due to the angular distribution restriction, as stated. Therefore, the comparison to previous data sets is also limited in this case. However, one observes that the data point of Lang et al. at $E_p = 65$ MeV appears to match excellently our $\sigma$-value at 66 MeV. In contrast, the data points taken over the proton energy range of $E_p = 23 - 50$ MeV by Narayanaswamy et al. [25] ($E_p = 23.7$ and 44.6 MeV), Lesko et al. [33] ($E_p = 30, 32, 40$ and 50 MeV), and Lang et al. [35] ($E_p = 40$ and 85 MeV) seem to overestimate the trend of our experimental values. The latter are well reproduced by nuclear reaction models via our TALYS calculations using modified OMP parameters (see next section). Regarding the 4.439 MeV line of $^{12}\text{C}$ produced via the $^{16}\text{O}(p, p')^{12}\text{C}$ reaction (see Fig. 13 (a)) our data set clearly appears to be in very good agreement with the experimental uncertainties with the previous data set of Lesko et al. [33] and the value of Lang et al. [35] over the explored common proton energy range, $E_p = 30 - 50$ MeV. They are also very consistent with the previous experimental data set from tandem accelerators below $E_p = 26$ MeV. For the two lines of $^{15}\text{O}$ and $^{15}\text{N}$ at $E_\gamma = 5.240$ and 5.269 MeV, respectively, previous data sets were measured at $E_p = 30 - 40$ MeV by Lesko et al. [33] and at $E_p = 40 - 85$ MeV by Lang et al. [35], while for the 2313 keV line of $^{14}\text{N}$ only data from the latter authors exist. As one can observe in Fig. (13) the previously reported values for these lines show a general agreement with our cross section curves with, however, some disagreement in the absolute values, in particular for the data of Lang et al. [35].

One can finally conclude that our experimental excitation functions for all the analyzed ten lines agree quite well, within the involved experimental uncertainties, with the previously reported cross section data sets, extending coherently the latter to higher proton energies up to $E_p = 200$ MeV.
5. Comparison of experimental γ-ray production cross sections to nuclear reaction models and to the Murphy et al. compilation, discussion.

5.1. TALYS code calculations, comparison to nuclear reaction model predictions

The nuclear reaction code TALYS [12] proved to be a very powerful tool for interpreting laboratory measured nuclear data such as nuclear reaction cross sections for fundamental research and various applications. It reliably predicts their values at energies out of reach to particle accelerators or where experimental data were missed [8]. EMPIRE2 [11] or TALYS were used for establishing nuclear data libraries [54, 55], for predicting nuclear reaction rates and related uncertainties, and chemical abundances in astrophysical media [53, 56, 57]. Several groups extensively used TALYS for reproducing γ-ray experimental cross sections [4, 5, 10, 33, 34] applied for modeling solar flares, the interactions of galactic LECRs, and calculating the total γ-ray emission fluxes from these sites [4, 5, 10]. Tatischeff, Koziolovsky, Kiener and Murphy [58] used both codes for calculating the delayed γ-ray line emission by radioactive ions produced in solar flares.

Cross sections can be calculated by TALYS for nuclear reactions induced by γ-ray, neutrons and charged particles (p, d, t, 3He and 4He) on various target nuclei over the energy range of $E_{lab} = 0.001 - 250$ MeV, based on main reaction mechanisms expected in this region (compound nucleus, direct reactions, pre-equilibrium, fusion-evaporation, etc.). In addition, the code includes libraries of input nuclear data (masses, level densities, discrete states, OMP and $\beta_3$ level deformation parameters, γ-ray branching ratios, strength functions, etc.) but allows the user to use instead values of these parameters either determined experimentally or derived by theoretical models. The user could then perform calculations with the default input parameters of TALYS or alternatively input one's own values (labelled modified parameters of TALYS) by means of provided keywords (in form of input files) or by editing the intrinsic nuclear data libraries of the code. We used the 1.6 version of TALYS, where experimentally known nuclear states are supposed to decay exclusively via γ-ray electromagnetic transitions. This version is suitable in the case of medium and heavy nuclei, where usually the first 25 states (the maximum number of states in TALYS, taken from experimental tables) are stable against particle emission and decay exclusively by electromagnetic transitions. Otherwise, for light target nuclei like $^{12}$C, for example, which has only one excited state below the alpha emission threshold, the user should modify the γ-ray branching ratios to take account of particle emission, or reduce the number of experimentally known states, explicitly used in the TALYS calculations.

We have first started calculating γ-ray production cross sections for the analyzed strongest lines of Tables 2-5 using the default input parameters of TALYS, introducing only the incident energy values and the (Z, A) properties of the projectile and targets. We obtained results that reproduced only the low-energy part of the experimental cross section data but considerably deviated from them elsewhere over wide energy domains, which led us to modify some default input data in TALYS. The required modifications concerned mainly the $\beta_3$ level deformation parameters for $^{12}$C, and the optical model potential parameters for both $^{12}$C and $^{16}$O target nuclei. In the case of the $^{12}$C target, we adjusted the OMP parameters such that the calculated cross sections reproduced the experimental data for the main line of $^{12}$C at $E_\gamma = 4.44$ MeV. The obtained modified OMP values (stored in an input file) were close to those extracted from the analyses [59, 60, 61, 62] of angular distributions for inelastic proton scattering, while we have taken the $\beta_3$ deformation parameters ($\beta_2$ = - 0.61, $\beta_4$ = 0.05) from Ref. [61]. We proceeded similarly in order to reproduce the main line of $^{16}$O at $E_\gamma = 6.129$ MeV. Notice that in the calculation of the theoretical cross sections for the 4.44 MeV line of $^{12}$C target, we summed the two components at $E_\gamma = 4.439$ MeV and 4.444 MeV (lines of $^{12}$C and $^{11}$B, respectively), since it was not possible to separate them experimentally. Then, we performed TALYS calculations of $\sigma(E_\gamma)$ with our modified OMP and $\beta_3$ level deformation parameters as input data (in addition to $E_\gamma$ and (Z, A) values of the reaction partners) for all the ten selected intense lines from Tables 2-5. The obtained results for the two main lines of $^{12}$C and $^{16}$O, taken as reference lines, are in excellent agreement with the experimental data, regarding both the energy dependencies and the absolute values of the experimental cross sections. Table 7 reports the modified OMP parameters used in our TALYS calculations, while we report in Figs. 10 and 13 the $\sigma(E_\gamma)$ excitation curves calculated by TALYS, together with the experimental data sets from the current and previous works. One can observe, in Figs. 10 and 13, that the theoretical results following the two calculation modes (default or modified) for the remaining eight analyzed lines from the two targets, at $E_\gamma = 0.718, 1.022$ MeV (of $^{10}$B), 2.000 MeV ($^{11}$C), 2.124 MeV ($^{11}$B), 2.313 MeV ($^{14}$N), 4.439 MeV ($^{12}$C), 5.240 MeV ($^{16}$O) and 5.269 MeV ($^{15}$N), agree fairly well, in general. The most noticeable differences appear only towards the high-energy region for the lines of $^{11}$C and $^{11}$B from the $^{nat}$C target and for the line of $^{15}$O from the Mylar target at $E_\gamma = 2.000, 2.124$ and 5.240 MeV, respectively. Besides, the comparison of TALYS-calculated excitation curves with corresponding experimental cross sections shows overall agreements, except for the two lines at $E_\gamma = 1.022$ MeV ($^{10}$B line from the C target) and $E_\gamma = 4.439$ MeV (line of $^{12}$C from the Mylar target via the $^{16}$O(p, p)$^{12}$C reaction) that exhibit substantial deviations between the calculated and measured absolute $\sigma$-values. Otherwise, while the agreement is quite good for the 0.718 MeV line of $^{10}$B from the $^{nat}$C target, significant deviations feature the other lines in
Figs. (11, 13) from the two irradiated C and Mylar targets. Table 8 lists the observed ratios between TALYS code–calculated cross sections and experimental data.

5.2. Comparison to the Murphy et al. compilation

Being of semi-empirical character, the compilation of Murphy, Kozlovsky, Kiener and Share [8] is based on the available (in 2009) experimental cross section data for main γ-ray lines from low-lying nuclear states, and on TALYS code [12] extrapolations to higher projectile energies where experimental data were missing. We also report in Figs. (10, 13) the cross section excitation curves predicted by this database [8] for comparison to σ(E_p) experimental data from the present and previous works.

One expects that regarding the lines for which previous experimental cross section data exist, the predicted cross sections should reproduce well the measured values. This is indeed true for the main line at E_γ = 4.439 MeV of ^12C produced in (p, p'γ) inelastic proton scattering reaction (see Figs. 11), showing that the semi-empirical curve from the Murphy et al. compilation [8] accounts quite well for nearly all the experimental data points including our values up to E_p = 200 MeV. Similarly, the semi-empirical curve for the 6.129 MeV line of ^16O from the (p, p'γ) reaction with this target nucleus seems to account well for most experimental data, including for our values at E_p = 125 and 150 MeV (see Fig. 12). However, the value of Lang et al. at E_p = 65 MeV and our values at E_p = 175 and 200 MeV are not reproduced by this curve. For the remaining four lines from the nat C target (Fig. 11), the derived semi-empirical curves agree reasonably well and better than the excitation curves predicted by TALYS with all the experimental data for the lines of ^10B, ^11C and ^11B at 0.728, 2.000 and 2.124 MeV, respectively, but not for the 1.022 MeV line of ^10B. Concerning the other four lines from the Mylar targets (see Fig. 13), one observes that for the 4.439 MeV line of ^12C from the ^16O(p, p'α)^12C reaction, the curve from the Murphy et al. compilation [8] reproduces very well the experimental data, including our values at E_p = 30, 42, 54 and 66 MeV. Then it overestimates our values for higher energies of up to E_p = 200 MeV. In comparison, the TALYS-predicted excitation curve describes our low-energy data up to E_p = 54 MeV, and deviates significantly from our data (by a factor of 2). The excitation curves derived for the 5.240 MeV line of ^15O both from the Murphy et al. compilation and via TALYS code calculation appear to be roughly consistent with experimental data. Besides, one observes that for the 2.313 and 5.269 MeV lines of ^14N and ^15N the predicted curves from the Murphy et al. compilation underestimate or overestimate, respectively, the experimental data beyond our value at E_p = 40 MeV, lying substantially farther below or above experiment. In contrast, the TALYS-calculated excitation curves for these two lines are much closer to experimental data, showing better consistency with the latter. More precisely, we provide quantitatively in Table 8 the observed differences between the γ-ray excitation functions predicted by the Murphy et al. compilation and by nuclear reaction models via TALYS code and experimental calculations cross section data.

6. Summary, discussion and perspectives

In summary, we report here new experimental γ-ray production cross sections for known main and other lines produced in proton-induced nuclear reactions on nat C and Mylar targets over the energy range, E_p = 30 - 200 MeV, using the SSC facility of iThemba LABS. These quantities were determined by fitting least squares Legendre polynomial expansions to the measured differential cross section angular distributions over the explored proton energy range. We also report line shape data measured versus E_p and θ_{lab} for the line complex observed at E_γ = 4.44 MeV in irradiations of both targets that was analyzed and discussed.

Figs. (10, 12) show that the measured cross sections for the prominent, main lines of ^12C and ^16O at 4.439 and 6.129 MeV are very well reproduced by TALYS code [12] calculations and the Murphy et al. compilation [8] over the wide proton energy range of E_p ≈ 6 - 200 MeV. This is also the case, to lesser extent, for the lines of ^10B and ^15O at E_p = 0.718 and 5.240 MeV, respectively. In addition, the TALYS-calculated and the Murphy et al. predicted excitation functions agree satisfactorily with the experimental data over the low-energy region below E_p = 30 MeV for all the other eight analyzed lines from the two targets, except for the 1.022 MeV line of ^10B from the nat C target.

This is not surprising since over this energy range, TALYS accounts very well for the involved, well formulated and implemented in this code, nuclear reaction mechanisms (compound nucleus, direct-reaction, pre-equilibrium models), while the semi-empirical compilation of Murphy et al. is partly based on those data. In contrast, significant deviations were observed between the experimental cross-section data and the values predicted by the TALYS calculations and the latter database at higher proton energies for several γ-ray lines (see Figs. (11, 13) and Table 8). As it has been confirmed in a recent study [62] of proton-induced reactions on Fe, Cu, and Ti from threshold to 55 MeV, state-of-the-art modern nuclear reaction modeling codes (ALICE, CoH, EMPIRE, TALYS) yield results that significantly differ from the cross section experimental data, particularly when default input parameters are used for
calculating their a priori predicted values. At high proton energies, one expects the $\gamma$-ray production cross sections to decrease smoothly with incident proton energy beyond the compound resonance maximum at $E_p \approx 20-30$ MeV, as can be observed here (see Figs. 10–13 and in our experimental cross section excitation functions reported in Ref. 10). Indeed, the ($p, p'\gamma$) inelastic scattering cross section comprises a number of different reaction mechanisms (compound nucleus, direct, pre-equilibrium, or fusion-evaporation reactions) that are strongly energy dependent. As the proton energy increases above $E_p = 30-40$ MeV, more and more nuclear reaction channels involving other reaction mechanisms (spallation, and even probably nuclear cascades) become successively open. This then makes it legitimate to suspect a still incomplete implementation of the reaction mechanisms in modern nuclear reaction codes at high energy.

These observations therefore lead one to suggest two ways in order to improve the predictions of the nuclear reaction models and obtain fair agreements between the measured experimental cross section data and the nuclear reaction theoretical models. (i) Using new and previous experimental cross section data, and (ii) preferentially using OMP level deformation and level density modified parameters in the calculation codes. For this purpose, one should extract reliable modified parameters from theoretical fits to elastic/inelastic experimental nucleon scattering data, as we did for the 4.439 and 6.129 MeV lines of $^{12}\text{C}$ and $^{16}\text{O}$. We have also systematically performed such detailed analysis for all the 41 $\gamma$-ray lines from the Mg, Si and Fe targets reported in Ref. 10 by means of the OPTMAN code [64] for coupled-channels nuclear reactions, obtaining fair agreements between TALYS predictions and the experimental data. In this respect, the realistic variation trends of the experimental $\gamma$-ray production cross sections for proton-induced reactions, including our new data sets (see Figs. 10–13 and Ref. 10) over the wide proton energy range, $E_p = 30$–$200$ MeV, should be usefully taken into account for better implementing these models in nuclear calculation codes [11, 10], particularly in TALYS. The determination of $\gamma$-ray production cross sections for other targets (Mg, Al, Si, Fe) abundant in astrophysical sites from our experimental campaigns over the proton energy range of $E_p = 66$–$200$ MeV, is being achieved. In the other hand, new experimental data sets have been recently reported by Kiener et al. [34] for $\alpha$-particle-induced reactions over the incident energy range of $E_p = 50$–$90$ MeV. Those data sets sometimes exhibit significant disagreements with TALYS code predictions and with the Murphy et al. compilation.

This points to the need of performing additional measurements of $\gamma$-ray production cross sections in both proton and $\alpha$-particle-induced reactions at the SSC facility of iThemba LABS in order to update and further enrich the existing data base [5]. They could consist in joint collaboration experiments devoted to better explore with more observation angles the important 6.129 MeV octupole main line of $^{16}\text{O}$ in proton-induced reactions over the energy range, $E_p = 30$–$110$ MeV, and for extending the recent data sets from Ref. 10 to higher $\alpha$-particle energies up to the maximum permitted value, $E_\alpha = 200$ MeV. To this end, one could take advantage of the recently upgraded AFRODITE array equipped with a new frame combining both clover and LaBr$_3$: Ce $\gamma$-ray detectors [65, 66]. This improved detection array of high-energy resolution and high efficiency would enable one to measure much more complete angular distributions for $\gamma$-ray lines of high multipolarity values than this was possible with the older detection array used in our experimental campaigns. The new $\gamma$-ray line production cross section results reported in this work have various applications including proton therapy and nuclear astrophysics. Concerning the latter topic, extending the previous low energy data up to $E_p = 200$ MeV, they will considerably increase the precision in the computed hadron-induced $\gamma$-ray flux below $E_p = 1$ GeV, then allowing precision modeling [67] of solar flare observational data reported by the Large Area Telescope onboard the Fermi satellite [68]. They would also help one elucidating the diffuse $\gamma$-ray emission induced in LECRs interactions with the gas and dust of the inner galaxy. One could then recalculate with higher accuracy the total nuclear $\gamma$-ray flux [4, 10] from these elusive interactions, the rate of the observed H$_2$ ionization in diffuse interstellar clouds [69], and maybe constrain the essentially undetermined spectrum of LECRs below 200 MeV/u [70]. In this context, the knowledge of $\gamma$-ray production cross sections in nuclear reactions from threshold up the highest possible energies of the accelerated particles delivered by laboratory particle accelerators is of great interest.

Acknowledgements

The authors are indebted to the technical staff of the iThemba LABS SSC accelerator for their kind help and friendly cooperation. Saad Ouichaoui expresses his thanks and is very grateful to Dr R. Nchodu for his warm welcoming of us throughout our experimental campaigns at the SSC facility of iThemba LABS. He also warmly thanks Dr F. Azaiez, current Director of iThemba LABS, for his kind hospitality.

This work has been carried out in the framework of a joint scientific cooperation agreement between the USTHB university of Algiers and iThemba LABS of Cape Town. The work was partially supported by the General Direction of Scientific Research and Technological Development of Algeria (project code A/ AS-2013-003), and by the National...
Research Foundation of South Africa under grants GUN: 109134 and UID87454. Besides, travel support was granted to the collaborating French researchers by the CSNSM and the IPN of Orsay (CNRS/IN2P3 and University of Paris-Sud). Thanks are due to all persons from these institutions who helped in the realisation of this project.

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### Tables

| Target                   | Thickness (mg cm\(^{-2}\)) | Areal density, N (atoms cm\(^{-2}\)) | Proton energies \(E_p\) (MeV); year | Observation angles (deg); year |
|--------------------------|----------------------------|--------------------------------------|-------------------------------------|-------------------------------|
| \(^{12}\)C \(^{16}\)O \(_{nat}\) | 8.40 ± 0.07               | 0.416 (4)\(\times\)10\(^{22}\)    | 30, 42, 54, 66; 2013.               | 85, 95, 130, 140; 2013 + 2015 |
|                          |                            | 0.416 (4)\(\times\)10\(^{22}\)    | 66, 80, 95, 110, 125; 2015.         | 85, 95, 130, 140, 166, 172; 2016 |
|                          |                            | 0.416 (4)\(\times\)10\(^{22}\)    | 66, 125, 150, 175, 200; 2016.       | 85, 95, 130, 140, 166, 172; 2016 |
| Mylar \((C_{10}H_8O_4)\) | 7.00 ± 0.08               | 0.219 (3)\(\times\)10\(^{22}\)    | 30, 42, 54, 66; 2013.               | 85, 95, 130, 140; 2013 + 2015 |
|                          |                            | 0.219 (3)\(\times\)10\(^{22}\)    | 66, 80, 95, 110, 125; 2015.         | 85, 95, 130, 140, 166, 172; 2016 |
|                          |                            | 0.219 (3)\(\times\)10\(^{22}\)    | 66, 125, 150, 175, 200; 2016.       | 85, 95, 130, 140, 166, 172; 2016 |

Table 1: Properties of the \(^{nat}\)C and Mylar targets used in the experiments with indication of the observation angles and years. The uncertainties on the last digits of their atomic surface density, N, are given in parentheses.

| \(E_\gamma\) (MeV) | Transition                    | Multipolarity | Reaction                      |
|--------------------|-------------------------------|---------------|-------------------------------|
| 0.718              | \(^{10}\)B, \(1^+\) 0.718 \(\rightarrow\) \(3^+\) g.s | E2            | \(^{12}\)C(p, X)\(^{10}\)B |
| 1.022              | \(^{10}\)B, \(0^+\) 1.740 \(\rightarrow\) \(1^+\) 0.718 | M1            | \(^{12}\)C(p, X)\(^{10}\)B |
| 1.436              | \(^{10}\)B, \(1^+\) 2.154 \(\rightarrow\) \(1^+\) 0.718 | M1+E2         | \(^{12}\)C(p, X)\(^{10}\)B |
| 2.000              | \(^{11}\)C, \(\frac{1}{2}^+\) 2.000 \(\rightarrow\) \(\frac{1}{2}^-\) g.s | M1            | \(^{12}\)C(p, X)\(^{11}\)C |
| 2.124              | \(^{11}\)B, \(\frac{1}{2}^-\) 2.125 \(\rightarrow\) \(\frac{3}{2}^-\) g.s | M1            | \(^{12}\)C(p, 2p)\(^{11}\)B |
| 2.154              | \(^{10}\)B, \(1^+\) 2.154 \(\rightarrow\) \(3^+\) g.s | E2            | \(^{12}\)C(p, X)\(^{10}\)B |
| 4.319              | \(^{11}\)C, \(\frac{5}{2}^-\) 4.319 \(\rightarrow\) \(\frac{3}{2}^-\) g.s | E2            | \(^{12}\)C(p, X)\(^{11}\)C |
| 4.439              | \(^{12}\)C, \(2^+\) 4.440 \(\rightarrow\) \(0^+\) g.s | E2            | \(^{12}\)C(p, p')\(^{12}\)C |
| 4.444              | \(^{11}\)B, \(\frac{5}{2}^-\) 4.445 \(\rightarrow\) \(\frac{3}{2}^-\) g.s | M1+E2         | \(^{12}\)C(p, 2p)\(^{11}\)B |
| 6.129              | \(^{16}\)O, \(3^-\) 6.130 \(\rightarrow\) \(0^+\) g.s | E3            | \(^{16}\)O (p, p')\(^{16}\)O |

Table 2: Properties of the \(\gamma\)-ray transitions observed in proton-induced nuclear reactions on the \(^{nat}\)C target are listed: the \(\gamma\)-ray energy (in the first column), the involved isotopes and the connected initial and final states, together with their J\(^{\pi}\) values (in the second column), the line multipolarity (in the third column), and the possible reaction channels leading to the emitting nucleus (in column 4). In the latter column, the light reaction products could be composed of different combinations of particles.
| $E_\gamma$ (MeV) | Transition | Multipolarity | Reaction |
|-----------------|------------|--------------|----------|
| 0.728           | $^{14}$N, $3^- \rightarrow 2^- \rightarrow 5.834 \rightarrow 2^- \rightarrow 5.106$ | M1+E2 | $^{16}$O(p, X)$^{14}$N |
| 1.635           | $^{14}$N, $1^+ \rightarrow 0^+ \rightarrow 3.948 \rightarrow 0^+ \rightarrow 2.313$ | M1 | $^{16}$O(p, X)$^{14}$N |
| 2.313           | $^{14}$N, $0^+ \rightarrow 2.313 \rightarrow 1^+_g s$ | M1 | $^{16}$O(p, X)$^{14}$N |
| 2.498           | $^{14}$N, $3^+ \rightarrow 1^+ \rightarrow 6.446 \rightarrow 1^+ \rightarrow 3.948$ | E2 | $^{16}$O(p, X)$^{14}$N |
| 3.684           | $^{13}$C, $\frac{1}{2}^- \rightarrow \frac{1}{2}^- \rightarrow 3.685 \rightarrow \frac{1}{2}^- \rightarrow g.s$ | M1+E2 | $^{16}$O(p, X)$^{13}$C |
| 3.853           | $^{13}$C, $\frac{5}{2}^- \rightarrow \frac{3}{2}^- \rightarrow 3.854 \rightarrow \frac{3}{2}^- \rightarrow g.s$ | M2+E3 | $^{16}$O(p, X)$^{13}$C |
| 4.439           | $^{12}$C, $2^+ \rightarrow 4.440 \rightarrow 2^+ \rightarrow g.s$ | E2 | $^{16}$O(p, X)$^{12}$C |
| 5.105           | $^{14}$N, $2^- \rightarrow 5.106 \rightarrow 1^+_g s$ | E1+M2+E3 | $^{16}$O(p, X)$^{14}$N |
| 5.240           | $^{15}$O, $\frac{5}{2}^- \rightarrow \frac{5}{2}^- \rightarrow 5.241 \rightarrow \frac{5}{2}^- \rightarrow g.s$ | M2+E3 | $^{16}$O(p, X)$^{15}$O |
| 5.269           | $^{15}$N, $\frac{5}{2}^- \rightarrow \frac{5}{2}^- \rightarrow 5.270 \rightarrow \frac{5}{2}^- \rightarrow g.s$ | M2+E3 | $^{16}$O(p, 2p')$^{15}$N |
| 6.129           | $^{16}$O, $3^- \rightarrow 6.130 \rightarrow 0^+ \rightarrow g.s$ | E3 | $^{16}$O(p, p')$^{16}$O |

Table 3: Same as in TABLE 2 but for the Mylar target. All the reactions in column 4 are induced on the $^{16}$O nucleus.

| $E_\gamma$ (MeV) | Origine |
|-----------------|---------|
| 0.198           | $^{76}$Ge(n, $\gamma$)$^{77}$Ge |
| 0.511           | $e^+e^-$ annihilation |
| 0.596           | $^{74}$Ge(n,n' $\gamma$)$^{74}$Ge |
| 0.689           | $^{72}$Ge(n,n')$^{72}$Ge |
| 0.834           | $^{72}$Ge(n,n' $\gamma$)$^{72}$Ge |
| 0.844           | $^{27}$Al(p,p' $\gamma$)$^{27}$Al |
| 0.868           | $^{74}$Ge(n,n' $\gamma$)$^{74}$Ge |
| 0.894           | $^{72}$Ge(n,n' $\gamma$)$^{72}$Ge |
| 1.014           | $^{27}$Al(p,p' $\gamma$)$^{27}$Al |
| 1.369           | $^{27}$Al(p, X)$^{24}$Mg |
| 1.612           | $^{27}$Al(p, X)$^{25}$Mg |
| 1.809           | $^{27}$Al(p,2p' $\gamma$)$^{26}$Mg |
| 2.212           | $^{27}$Al(p,p' $\gamma$)$^{27}$Al |
| 2.754           | $^{27}$Al(p,$\alpha$ $\gamma$)$^{24}$Mg |
| 3.004           | $^{27}$Al(p,p' $\gamma$)$^{27}$Al |

Table 4: Background $\gamma$-ray lines produced in proton beam interactions with surrounding materials (Al, Ge) forming the reaction chamber and HP-Ge detectors.
Table 5: List of $a_\ell$ coefficients obtained from Legendre polynomial expansion (Eq. 4) fits to the experimental $\gamma$-ray angular distributions.

Table 6: Experimental values and related uncertainties of integrated cross sections for the identified ten most intense $\gamma$-ray lines emitted in proton irradiations of the $^{nat}C$ and Mylar targets (see the text in Subsection 3.4.2 for more details).
### Parameters

| Parameters | \(^{12}\text{C}\) | \(^{16}\text{O}\) |
|------------|-----------------|-----------------|
| \(E_f\) (MeV) | -8.95 | -6.36 |
| \(r_v\) (fm) | 1.162 | 1.162 |
| \(a_v\) (fm) | 0.665 | 0.665 |
| \(V_1\) (MeV) | 55.4 | 99.8 |
| \(V_2\) (MeV\(^{-1}\)) | 0.007 | 0.007 |
| \(V_3\) (MeV\(^{-2}\)) | 0.000027 | 0.000022 |
| \(W_1\) (MeV) | 15.20 | 15.20 |
| \(W_2\) (MeV) | 85.0 | 75.0 |
| \(r_{vd}\) (fm) | 1.29 | 1.29 |
| \(a_{vd}\) (fm) | 0.51 | 0.51 |
| \(d_1\) (MeV) | 14.60 | 14.60 |
| \(d_2\) (MeV\(^{-1}\)) | 0.0224 | 0.0224 |
| \(d_3\) (MeV) | 11.50 | 11.50 |
| \(r_{vso}\) (fm) | 1.0 | 1.0 |
| \(a_{vso}\) (fm) | 0.58 | 0.58 |
| \(V_{vso1}\) (MeV) | 9.50 | 6.0 |
| \(V_{vso2}\) (MeV\(^{-1}\)) | 0.0136 | 0.0035 |
| \(W_{vso1}\) (MeV) | -3.1 | -3.1 |
| \(W_{vso2}\) (MeV) | 160.0 | 160.0 |

Table 7: Adjusted values of the OMP parameters used as modified input data in TALYS code calculations of \(\gamma\)-ray production cross sections for proton reactions with \(^{12}\text{C}\) and \(^{16}\text{O}\) target nuclei.

### Table 8: Ratios of \(\gamma\)-ray production cross sections calculated by TALYS or derived from the Murphy et al. compilation [8] to experimental data for two proton beam energies, \(E_p = 66\) and 150 MeV.

| \(E_{\gamma}\) (MeV) | TALYS/Experiment | Murphy et al./Experiment |
|---------------------|------------------|--------------------------|
|                     | \(E_p = 66\) MeV | \(E_p = 150\) MeV       | \(E_p = 66\) MeV | \(E_p = 150\) MeV |
| \(p + \text{n}\)    |                  |                          |                   |
| 0.718               | 2.41             | 0.98                     | 1.96              | 1.07             |
| 1.022               | 4.83             | 2.50                     | 5.71              | 4.15             |
| 2.00                | 1.05             | 0.37                     | 1.34              | 1.21             |
| 2.124               | 1.78             | 0.51                     | 1.74              | 1.25             |
| 4.44                | 1.11             | 1.05                     | 1.07              | 1.10             |
| \(p + \text{Mylar}\)|                  |                          |                   |
| 2.313               | 0.75             | 0.41                     | 0.40              | 0.18             |
| 4.439               | 2.22             | 5.88                     | 1.10              | 2.37             |
| 5.240               | 0.83             | 0.57                     | 1.28              | 1.18             |
| 5.270               | 1.93             | 1.39                     | 3.27              | 3.25             |
| 6.129               | 0.99             | 0.83                     | 1.69              | 0.84             |
Figure 1: Schematic diagram of the experimental set up, showing the AFRODITE reaction chamber traversed by the incident proton beam within the beam pipe and the associated γ-ray clover detection array in the configuration used.
Figure 2: $\gamma$-ray energy spectra from radioactive sources placed at the target position, recorded by a HP-Ge detector located at $\theta_{\text{lab}} = 95$: (a) $^{152}$Eu source and (b) $^{60}$Co source. The spectra resulting from a GEANT4 simulation with a detailed model of the experimental configuration and all the disintegration $\gamma$-ray lines from the $^{152}$Eu and $^{60}$Co radioactive sources are also plotted. The sum peaks from coincidence-cascades between full-absorption energy photons have negligible intensities relative to these lines both in the experimental and in the GEANT4-simulated energy spectra.
Figure 3: Experimental and GEANT4-simulated absolute detection efficiencies versus the $\gamma$-ray energy from a single HP-Ge crystal placed at $\theta_{\text{lab}} = 85^\circ$ in the 2015 experiment. The fitted curve to the data is represented with a $\pm 12\%$ uncertainty shown by dotted lines. For the normalization of the simulated values to the experimental data, see the text in subsection 3.1.
Figure 4: $\gamma$-ray energy spectra recorded by two HP-Ge detectors in proton irradiations: (a) of the $^{nat}$C target for $\theta_{lab} = 130^\circ$, $E_p = 54$ MeV, and (b) of the Mylar target for $\theta_{lab} = 85^\circ$, $E_p = 150$ MeV. Each figure comprises three spectra for the corresponding target: - in red color: raw experimental spectrum with target exposed to the proton beam - in purple: background spectrum with beam but without target in place, normalized to the same accumulated charge, - in blue: obtained net spectrum after background subtraction.
Figure 5: $\gamma$-ray energy spectra spectrum from an HP-Ge detector located at $\theta_{\text{lab}} = 130^\circ$ in the irradiation of the $^{nat}$C target with a proton beam of 54 MeV after subtraction of the Compton background and the components for the escape lines. The $\gamma$-ray lines of interest listed in TABLE 4 and the background lines from TABLE 4 are indicated by their corresponding energies in keV.
Figure 6: Similar to Fig. 5 for a HP-Ge detector located at $\theta_{\text{lab}} = 85^\circ$ but in irradiation of the Mylar target with a proton beam of 150 MeV. The γ-ray lines of interest listed in TABLES 2 and 3 and the background lines from TABLE 4 are indicated by their corresponding energies in keV.
Figure 7: γ-ray profiles (counts per channel versus the proton beam energy $E_p$ and the observation angle $\theta_{\text{lab}}$) for the line complex observed at $E_\gamma = 4.44$ MeV in proton irradiation of the $^{nat}$C target. The experimental profiles are depicted in red color, while the calculated profiles for the line of $^{11}$C at $E_\gamma = 4.319$ MeV produced in inelastic proton scattering are represented in blue (see text).
Figure 8: Measured profiles versus the proton beam energy ($E_p$) and the observation angle ($\theta_{lab}$) for the line complex at $E_\gamma = 4.44$ MeV after subtraction of the component for the 4.319 MeV line of $^{11}$C. The six panels (a), (b), (c), (d), (e) and (f) correspond to the proton beam energies $E_p = 30$, 54, 80, 110, 150 and 175 MeV, respectively.
Figure 9: Examples of measured $\gamma$-ray differential cross section angular distributions (blue symbols) and Legendre polynomial expansion fits (red curves): (a) data for the line of $^{12}$C at $E_\gamma = 4.44$ MeV, (b) data for the line of $^{16}$O at $E_\gamma = 6.129$ MeV.
Figure 10: Integral cross section excitation functions for the 4.44-MeV $\gamma$-ray line produced in inelastic proton scattering off the $^{12}$C target. The experimental data are shown by colored symbols: in red (this work), blue (Dyer et al.), green (Orsay group), magenta (Lang et al.), black (Lesko et al.). The blue curve corresponds to the predictions of the Murphy et al. semi-empirical compilation (Ref. [8]). The black curve represents the results derived by TALYS calculation with default input parameters, while the red curve refers to TALYS calculations with our modified OMP and $\beta$ deformation parameters.
Figure 11: Excitation functions for four other $\gamma$-ray lines emitted in proton interactions with the $^{nat}$C target, using the same symbols as in Fig. 10. Our experimental results for the lines of $^{11}$C and $^{11}$B at $E_\gamma = 2.000$ and 2.124 MeV, respectively, are compared to Lang et al. [35] data.
Figure 12: Same as in Fig. 10 but for the 6.129-MeV main line of $^{16}$O produced in proton irradiation of the Mylar target. In addition, the black circles represent the Narayanaswamy et al. [25] data.
Figure 13: Same as in Fig. 11 but for four other γ-ray lines emitted in proton interactions with the Mylar target, using the same symbols as in Fig. 10. Our experimental results are compared to existing previous data.