# New γ-ray production cross sections for the 4.439 and 6.129 MeV lines of $^{12}$C and $^{16}$O. Astrophysical implications

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**Abstract**. Gamma-ray line production cross sections from nuclear reactions induced by 30 - 200 MeV protons on $^{nat}$C and Mylar targets have been measured at the SSC facility of iThemba LABS. Results for the 4.439 and 6.129 MeV prominent lines of $^{12}$C and $^{16}$O of astrophysical concern are reported and discussed.

## 1. Introduction

Solar flares (SFs) and the interstellar medium (ISM) are respectively seats of strong luminosity changes due to sudden bursts of electromagnetic energy and violent nuclear reactions induced by low-energy cosmic rays (LECRs) in the galaxy. Measuring γ-ray production cross sections with particle accelerators allows one to simulate the processes at work in these sites, to extract information on the properties of the latter, and to elucidate the acceleration mechanisms of cosmic particles. The 4.439 and 6.129 MeV lines of $^{12}C$ and $^{16}O$ are among the strongest lines observed in SFs. We have recently measured [1, 2] their cross sections at the SSC facility of iThemba LABS using the previous AFRODITE detection array. In this contribution, we compare the obtained results to available counterparts, to the predictions of the TALYS code [3] and of a semi-empirical compilation [4].

## 2. Experiments, data analysis, results and discussion

Detailed descriptions of the experimental set up and the data analysis can be found in Refs. [1, 2]. (30 – 200 MeV proton beams with current intensities of 2-5 nA were focused onto a $^{nat}C$ and a Mylar targets placed under high vacuum at the centre of the AFRODITE reaction chamber. The associated γ-ray detection array composed of 8 Compton-suppressed clover detectors was used for measuring the γ-ray angular distributions. The energy calibration and the detection efficiencies were determined using calibrated radioactive sources of $^{60}Co$, $^{137}Cs$ and $^{152}Eu$ over the energy range of $E_\gamma$ = 0.122– 1.408 MeV. Then efficiency values were Monte-Carlo simulated over the energy range of $E_\gamma$ = 0.08 - 10 MeV using the GEANT4 software [5] and normalized to experimental data. The overall uncertainty in the detection efficiencies amounted to at most 12%.

Good statistics with count rates of 5-6 kHz from the HP-Ge crystals allowed an easy treatment of the raw experimental data in the single crystal mode with correcting the count rates for dead time events. The γ-ray line peaks in the energy spectra were analysed by the gf3[6] program, extracting their line peak count integrals by symmetric Gaussian-shape fits to the data and subtracting the related background by linear fits, except in the case of Doppler effect-broadened γ-ray line complexes that required a special treatment (see the contribution by Y. Rahma et al.).

### 2.1 γ-ray energy spectra and transitions

Fig. 1 reports an experimental γ-ray energy spectrum from the Mylar target corrected for backgrounds.

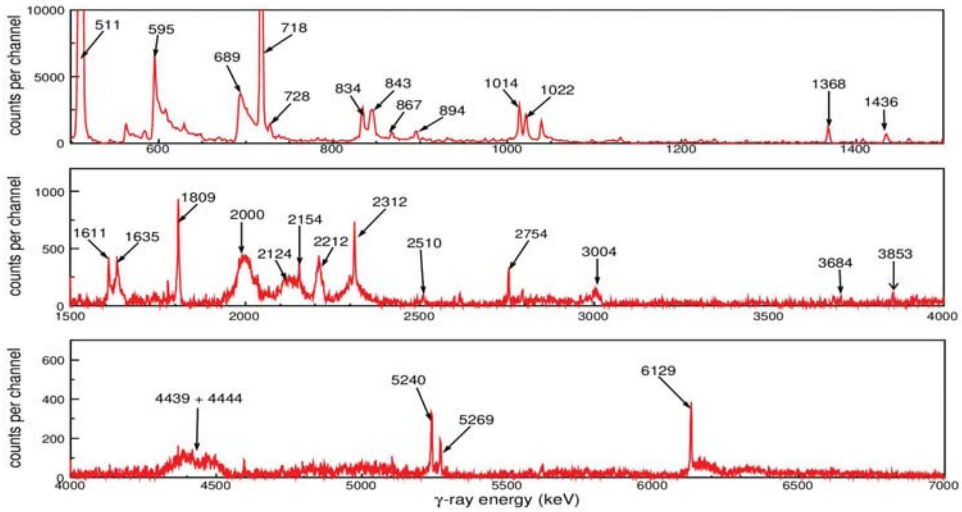


**Figure 1.** γ-ray energy spectrum from a HP-Ge detector set at $\theta_{lab}$= 85° in irradiation of the Mylar target with 150 MeV protons after subtraction of the Compton background and the components for escape lines. The γ-ray lines of interest and background lines are indicated by their energies in keV unit.

The recorded γ-ray energy spectra exhibit several γ-ray lines of various shapes and strengths emitted by different isotopes, some lines being broadened and shifted by Doppler effect. Notably, the lines at $E_\gamma$ = 4.439 and 6.129 MeV referring to the E2 ($J^\pi = 2^+$, 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) reactions, undergo strong Doppler broadening (≈ 150 keV for the 6.129 MeV line) making them good candidates for line shape analyses [7, 8]. We identified several γ-ray transitions with multipolarity values not exceeding λ = 3, corresponding to the de-excitation of low-mass isotopes ($^{10, 11}$B, $^{11, 12, 13}$C, $^{14, 15}$N, $^{15, 16}$O) produced in proton reactions with $^{12}$C and $^{16}$O. Background line peaks from the environment material ($^{27}$Al, Ge isotopes) were also observed. Line peaks from Ge grow at $E_\gamma$ = 198.39, 595.85, 689.60, 834.01 and 0.894 keV, while from $^{27}$Al one has peaks at 843.76, 1.014 MeV, 1.368 MeV.

### 2.2 γ-ray production cross-sections, comparison to previous data sets

The angle-integrated γ-ray line production cross sections were determined from the zero-order coefficients of Legendre polynomial expansion fits to the measured angular distribution differential cross sections that were affected by an overall average relative uncertainty of ~17%. Several γ-ray lines of interest growing in the energy spectra are intense enough to allow extracting the corresponding integral cross sections. The obtained $\sigma$ ($E_p$) experimental data sets for the two lines of $^{12}$C at $E_\gamma$ = 4.44 MeV (a complex dominated by the 4.439 MeV line) and $^{16}$O at 6.129 MeV are reported in Figs. (2, 3), respectively. We derived overall mean relative uncertainties of 18-25% in the case of isolated narrow lines, and values in the range of 20 - 30% for overlapped, Doppler-broadened lines.

One can observe in Figures (2, 3) that previously reported experimental data sets for the two main lines of $^{12}$C and $^{16}$O cover essentially the low proton energy region of $E_p \leq$ 26 MeV, dominated by the compound resonance structure around $E_p$ = 15 – 20 MeV. They were measured with tandem accelerators by the Washington [9-12] and Orsay [7, 13-16] groups, while only few data points were taken at higher proton energies with cyclotrons [17, 18]. Our experimental $\sigma$ ($E_p$) data sets for these two lines of astrophysical importance show general good agreement with the previously reported cross section data sets, extending coherently the latter to higher proton energies up to $E_p$ = 200 MeV.

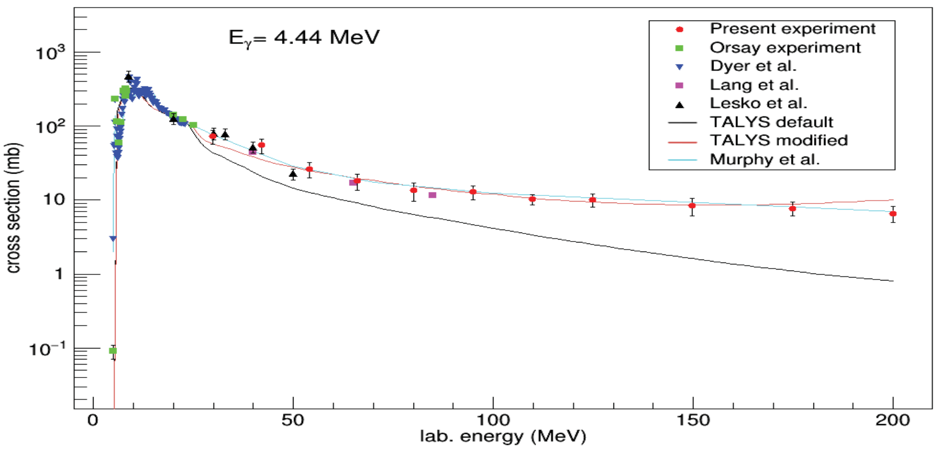


**Figure 2.** Cross sections for the 4.44-MeV line produced in inelastic proton scattering off the $^{nat}$C target. Data from this work are shown in red color, in green (data from the Orsay group [**7**, 13-16]), in blue (data of Dyer et al. [9]), in magenta (data of Lang et al. [17]), in black (data of Lesko et al. [18]). Green curve (Murphy et al. compilation [4]), black curve (TALYS code [3] calculations with default parameters, red curve (TALYS code calculations with our modified OMP and $\beta_\lambda$ deformation parameters).

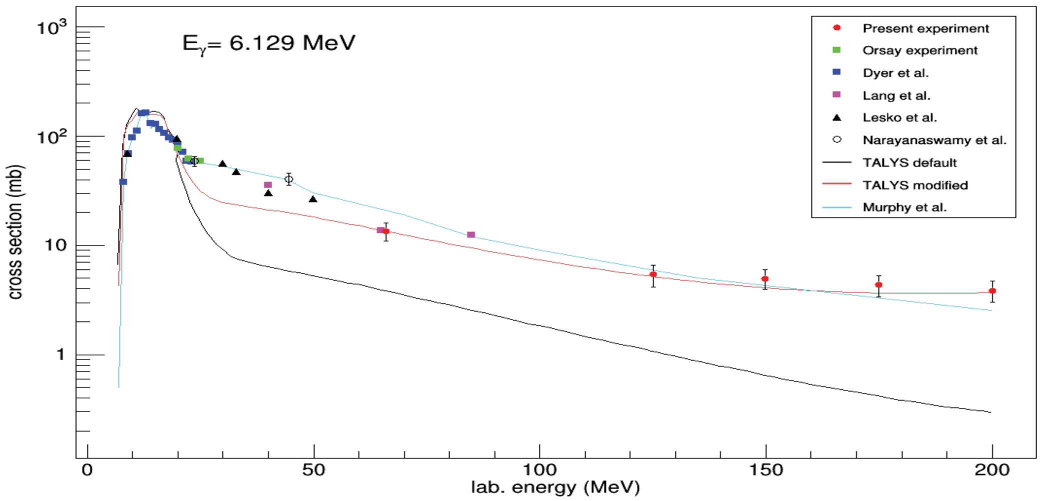


**Figure 3.** Same as in Figure 2, but for the 6.129-MeV main line of $^{16}$O from the Mylar target. Black circles (data from [10]).

## 3. Comparison of experimental $\sigma$ (E$_p$) data to nuclear reaction models and to the Murphy et al. compilation

TALYS code [3] calculations were first performed using the default input parameters of this code. The obtained results reproduced the resonant low proton energy part of the experimental data but significantly deviated from the latter elsewhere over wide energy domains, as shown in Figs. (2, 3). We then performed calculations using our input data of TALYS to obtain $\beta_\lambda$ level-deformation parameters for $^{12}$C and optical model potential (OMP) parameters for both two $^{12}$C and $^{16}$O target nuclei. In the calculations for the 4.44 MeV line of $^{12}$C, we summed the two components at $E_\gamma = 4.439$ MeV and 4.445 MeV since it was not possible to separate experimentally these lines of $^{12}$C and $^{11}$B. The obtained results for the two main lines of $^{12}$C and $^{16}$O are in excellent agreement with experimental data (see Figures (2, 3)).

Besides, very good agreements are also obtained between the experimental $\sigma$ (E$_p$) data and the values predicted by the semi-empirical compilation of Murphy et al. [4].

## 4. Conclusion and perspectives

The current and previous experimental data sets are well reproduced by TALYS code [3] calculations using modified nuclear level-deformation and OMP parameters, and are also in good agreement with the Murphy et al. semi-empirical compilation [4] over the wide proton energy range of $E_p \approx 6$ - 200 MeV.

Future experiments with proton and α-particle projectiles could be performed at the SSC facility using the upgraded AFRODITE detection array allowing more complete angular distributions.

Regarding astrophysical applications, the reported cross section data will increase the precision in the computed hadron-induced γ-ray flux below $E_\gamma = 1$ GeV, then allowing correct modeling [19] of solar flare data reported by the LAT device onboard the Fermi satellite. They would also help elucidating the diffuse γ-ray emission induced in interactions of LECRs with the gas and dust of the inner galaxy. One could then recalculate with higher accuracy the total nuclear γ-ray flux [1, 20] from these elusive interactions, the rate of the observed $H_2$ ionization in diffuse interstellar clouds, and maybe constrain the essentially undetermined spectrum of LECRs below 200 MeV/u.

**References**

[1] W Yahia-Cherif et al., PhysRev C, **102**, 025802 (2020)
[2] Y. Rahma, S. Ouichaoui, J. Kiener, E.A.Lawrie, J.J. Lawrie, V. Tatischeff, A. Belhout et al., Nuclear Physics A 1032 (2023) 122622.
[3] A J Koning, S Hilaire, and M C Duijvestijn, in *International Conference on Nuclear Data for Science and Technology*,Nice, France, edited by E. R. O. Bersillon, F. Gunsing, and S.Leray (EDP Sciences, Les Ulis, France, 2008), pp. 211–214.
[4] R J Murphy et al.,Astrophys. J. Suppl. Ser. 183, 142 (2009).
[5] GEANT4, http://geant4.web.cern.ch/.
[6] R C Radford, https://radware.phy.ornl.gov/.
[7] H Benhabiles-Mezhoud*et al.*,Phys. Rev. C 83, 024603 (2011).
[8] J Kiener, Phys. Rev. C 99, 014605 (2019).
[9] P Dyer et al., Phys. Rev. C 23, 1865 (1981).
[10] J Narayanaswamy, P Dyer, S R Faber and Sam M Austin, Phys. Rev. C 24, 2727 (1981).
[11] A G Seamster et al., Phys. Rev. C 29, 394 (1984).
[12] P Dyer et al., Phys. Rev. C 32, 1873 (1985).
[13] A Belhout et al., Phys. Rev. C 76, 034607 (2007).
[14] H Benhabiles-Mezhoud, Ph.D. thesis, Université Paris-Sud, Orsay, 2010.
[15] J Kiener et al., in *Proceedings of the DAE Symposium on NuclearPhysics* (Bhabha Atomic Research Centre, Roorkee, India, 2008), Vol. 53.
[16] J. Kiener et al. Phys. Rev. C 58, 2174 (1998).
[17] F L Lang et al., Phys. Rev. C 35, 1214 (1987).
[18] K T Lesko et al., Phys. Rev. C 37, 1808 (1988).
[19] Ervin Kafexhiu et al., The Astrophysical Journal, 864:148 (9pp), 2018 September, 10.
[20] H. Benhabiles-Mezhoud et al., The Astrophysical Journal, 763:98 (8pp), 2013 February 1.