Shape analysis of the 4.44 MeV γ-ray line complex produced in inelastic proton scattering off ^{12}C over the indent energy range of E_p = 30–200 MeV

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Abstract. We report γ-ray spectra for the line observed at E_γ = 4.44 MeV in our previous experiments at iThemba LABS' SSC facility using 30 - 200 MeV proton beams to irradiate a ^{nat}C target. It is actually a complex composed of several lines of interest broadened by Doppler effect. In addition to the dominant 4.439 MeV line of ^{12}C, two other lines at E_γ = 4.319 and 4.445 MeV assigned to ^{11}C and ^{11}B, respectively, are significant components of this complex. The analysis of its line shapes based on nuclear reaction models is the main topic of this contribution.

1. Introduction

The interaction of energetic particles with ambient matter in astrophysical sites (solar flares, the interstellar medium) produces nuclear γ-ray lines with energies from tens of keV to about 20 MeV, emitted by residual nuclei during their de-excitation. These lines are of great richness in spectral structure depending on the composition and energy of the accelerated particles as well as the composition and physical state of the ambient medium [1] on which valuable information can be inferred from the study of the emitted γ-rays, especially from line shape analyses [2]. In recent experiments carried out in joint collaboration at the SSC facility of iThemba LABS using the AFRODITE clover detection array of high energy resolution and high efficiency, we pointed out [3, 4] γ-ray line complexes in the recorded γ-ray energy spectra importantly Doppler-broadened and shifted. Their line shape analysis revealed them to be composed of lines from different de-exciting isotopes. Detailed descriptions of the experimental set up and methods used can be found in Refs. [3, 4]. Here, we report on our treatment of a line complex observed at E_γ = 4.44 MeV in proton irradiations of a natural C target.

2. Data analysis and results

The recorded raw γ-ray energy spectra show that the suppression of the Compton background by the BGO crystals is not complete. Many lines of various shapes and intensities are observed in the spectra, in particular a broad structure at E_γ = 3.3 - 4.6 MeV. It is actually a complex region composed of several γ-ray lines broadened by Doppler effects, as well as their Compton components and their escape peaks. In this case, the integration of the area under the peak of full photoelectric absorption requires a special treatment. The line profiles and their integrals could only be obtained from the deconvolution of the γ-ray energy spectra. The Compton scattering and escape line contributions were subtracted by means of energy-deposition γ-ray spectra in the HP-Ge crystals of the detection configuration simulated with the GEANT4 toolkit for a wide range of γ-ray energies of E_γ = 500–7000 keV. A cleaned γ-ray energy spectrum is reported in Figure 1. Nuclear reaction code calculations predict that the 4.439 MeV line of ^{12}C is the only component below the proton beam energy of E_p = 25 MeV, while above this energy the 4.445 MeV line of ^{11}B contributes significantly via the $^{12}C(p,2p)^{11}B$ reaction, as well as the 4.319 MeV line of ^{11}C via the $^{12}C(p,pn)^{11}C$ reaction. Some minor components such as the 4.339 MeV line of ^{11}C and the 4.444 MeV line of ^{10}B are also probably present.

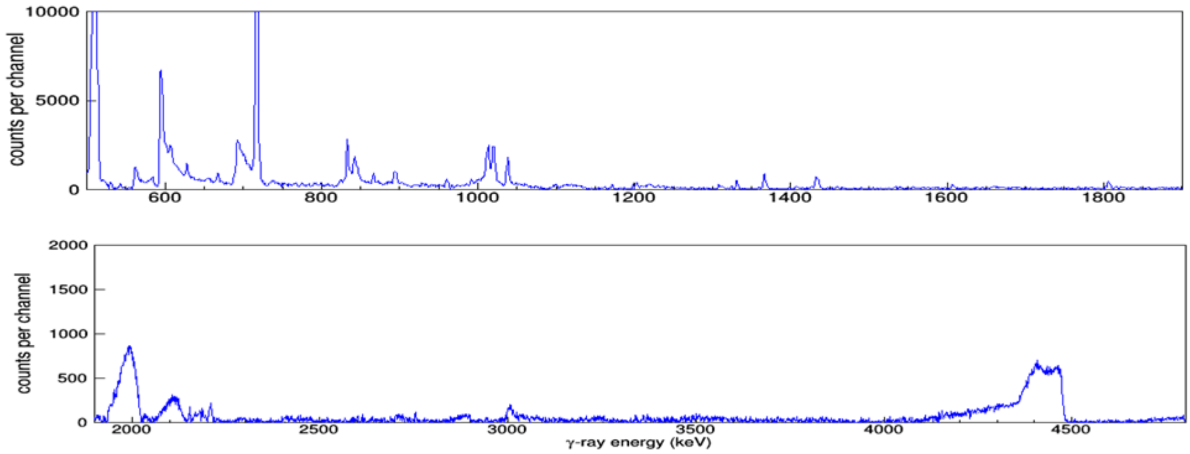

Figure 1. γ-ray energy spectrum from a single HP-Ge detector located at θ_{lab} = 130° in the irradiation of the ^{nat}C target with a proton beam of energy E_p = 54 MeV after subtraction of the Compton background and the escape line contributions. The energy resolution of the detection system, determined relative the 1332 keV line of a ^{60}Co radioactive source, amounted to at most 0.19%.

In these circumstances, the determination of the γ-ray line peak contents at full photon energy absorption demands a particular treatment. We were therefore led to perform a meticulous spectral deconvolution concerning the peak associated with the line from ^{11}C at $E_\gamma = 4.319$ MeV appearing on the left hand side of the line complex at $E_\gamma = 4.44$ MeV (see Fig. 2). For this purpose, we generated the corresponding theoretical spectral form as follows. We subtracted the Compton background and the escape line peak components. We derived the contribution of the line at 4.319 MeV after calculating its line shape according to the method described in Ref. [5]. To this end, we used a Monte Carlo simulation program written by Kiener [6] taking into account the geometry and energy resolution of the HP-Ge detector. We used as input data for the $^{12}C(p,pn)^{11}C$ 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 that the slowing down in the target of the ^{11}C isotope in its excited state ($\tau < 8.3$ fs) occurs with an exponentially decreasing probability of γ-ray emission, and evaluated the stopping power of the target by the SRIM code.

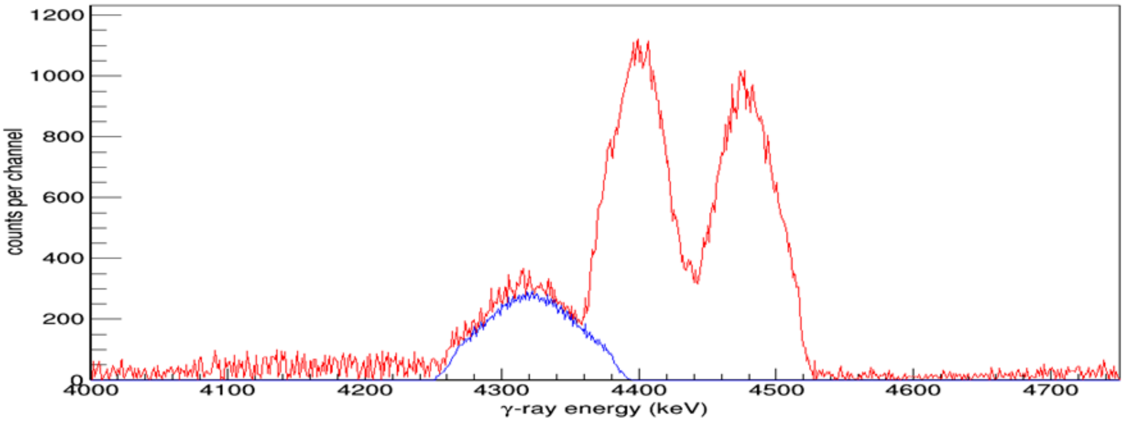

Figure 2. γ-ray profile for the 4.44-MeV line complex observed at $\theta_{lab} = 85°$ during the irradiation of the ^{nat}C target by a 30 MeV proton beam. The experimental profile is shown in red colour, while the profile calculated for the line of ^{11}C at $E_\gamma = 4.319$ MeV is shown in blue.

The evolution of the profile of the line 4.44 MeV complex versus θ_{lab} after subtraction of the 4.319 MeV line component of ^{11}C is reported in Fig. 3. Observing Figs. (2, 3) above and Figs. (7, 8) in Ref. [4], one can note striking changes in the shape of this line complex with varying both θ_{lab} and E_p. Indeed, the 4.44 MeV line complex resulting from the $^{12}C(p,p')^{12}C$ nuclear reaction **was** visible in the γ-ray spectra recorded at angles of $\theta_{lab} = 90° \pm 5°$ in form of a double bump (see Fig. 1) both from the ^{nat}C and the Mylar targets (see Figs. (5, 6) of Ref. [4]). The center of the valley between the two peaks corresponds to the energy $E_\gamma = 4439$ keV (dominant line of ^{12}C). Then, the double peak becomes asymmetrical and offset when the detection angle is varied (see Fig. 3). The explanation of its shape lies in the interaction of the Doppler effect and the selective population of magnetic sublevels of the first excited state of ^{12}C during the process of inelastic scattering. It was proved by Kolata et al. [7] that the kinematic effect itself, in the absence of the selective population of magnetic sublevels, could not produce the double-peak structure of the carbon line. This phenomenon has also been observed in the recorded gamma-ray spectra from solar flares [8].

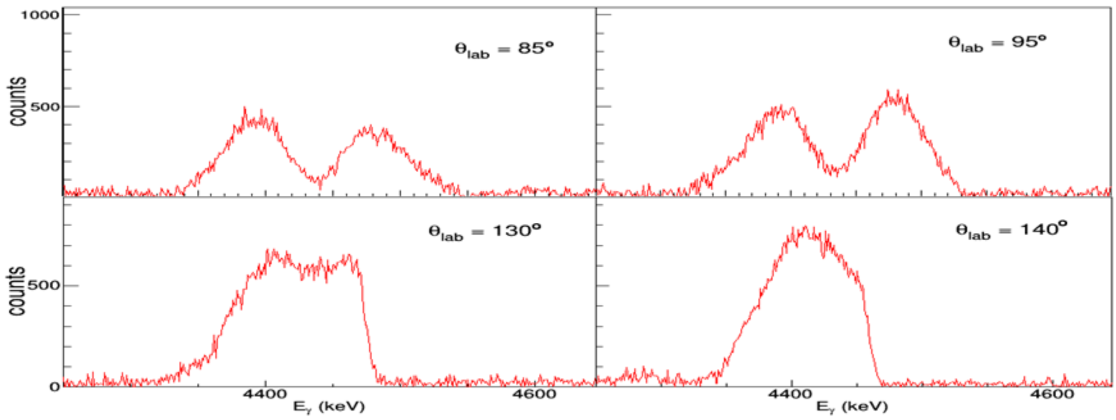

Figure 3. γ-ray energy spectra measured at a proton beam energy of E_p = 54 MeV, showing the evolution of the profile of the line complex at E_γ = 4.44 MeV versus the observation angle after subtraction of the component for the 4.319 MeV line of ^{11}C,

3. Conclusion

The availability of the present and previous reliable experimental line shape data over a wide proton energy range extending and their interpretation in terms of nuclear reaction models [2] makes it possible to envisage their relevant application in nuclear astrophysics. This would provide a better understanding of the complex interaction processes occurring in various astrophysical sites, of the properties of these sites and of the acceleration mechanisms of the cosmic particles.

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