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To cite this article: Sergio Szpigel *et al* 2022 *J. Phys.: Conf. Ser.* **2340** 012031

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Journal of Physics: Conference Series 2340 (2022) 012031 doi:10.1088/1742-6596/2340/1/012031

Monte Carlo simulations of nuclear de-excitation gamma-ray line spectra from solar flares

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Abstract. Recently, we have demonstrated that the Monte Carlo package FLUKA can be used as an effective tool for simulating nuclear processes which occur in solar flares and that it is capable to provide a self-consistent treatment of all typical components of the γ-ray spectra observed in those events. In this work, we have employed a new simulation strategy that allows to improve statistics and resolution in energy of the generated γ-ray spectra. Using this new strategy, we have calculated spectra of γ-ray nuclear de-excitation lines produced by solar flare primary accelerated ions with typical power-law energy distributions.

1. Introduction

The modelling of solar flare γ-ray spectra is generally performed through the fitting of observed data using a set of templates and standard functions for the spectral components produced by the several relevant physics processes: bremsstrahlung of positrons and electrons, nuclear de-excitation, neutron capture, electron-positron annihilation and decay of pions [1, 2]. In particular, a comprehensive investigation on the production of γ-ray nuclear de-excitation lines in solar flares was performed by Ramaty et al.[3], which resulted in the development of a code for the Monte Carlo calculation of spectra of solar flare γ-ray nuclear de-excitation lines, including the components from the direct and inverse nuclear reactions and the unresolved component. An updated and improved version of this code (here called RMK) was developed by Kozlovsky, Murphy, and Ramaty [4] and Murphy et al. [5] including new cross sections from laboratory measurements and calculations with the code for nuclear reactions TALYS [6]. Templates for spectra of γ-ray nuclear de-excitation lines built with the RKM code are available in the spectral analysis software package Objective Spectral Executive (OSPEX) [7].

FLUKA [8] is a package of fully-integrated routines for the Monte Carlo simulation of the transport and the interactions of particles in matter. In recent works [9, 10], we have demonstrated that FLUKA can be used as an effective tool for simulating nuclear processes which occur in solar flares and that it is capable to yield a self-consistent treatment of all typical components of the γ-ray spectra observed in those events in the range from hundreds of keV to hundreds of MeV. In this work, we have employed a new simulation strategy that allows to enhance the statistics and resolution in energy of the generated γ-ray spectra. Using this new strategy, we have calculated spectra of γ-ray nuclear de-excitation lines produced by solar flare primary accelerated ions with typical power-law energy distributions.

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2. Solar flare model

In our simulations with FLUKA we setup a simple model for solar flares in which primary accelerated ions (protons, ^{3}He and α-particles) precipitate into a thick-target with characteristics similar to those of the solar atmosphere. We adopt a plane-parallel geometry, since in general the dimensions of the solar flare region where the ions interact and the emission of radiation occurs are much smaller than the solar radius. As shown in Figure 1, we consider a cubic box centered at the origin of a system of Cartesian coordinates (Ox, Oy, Oz) with edges of length 2L = 2 × 10^9 cm. The z-coordinate stands for the vertical depth in the solar atmosphere.

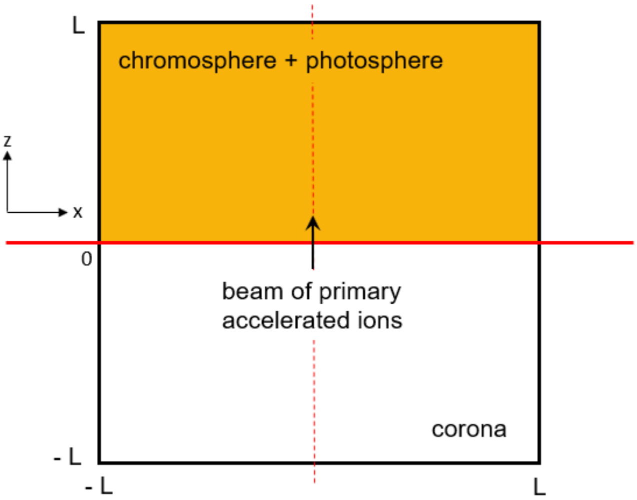

Figure 1. Two-dimensional representation of the geometry adopted for the ambient solar atmosphere.

The cubic box is divided into two regions by a (xy)-plane at z = 0. The region z < 0 corresponds to the coronal layer and, for simplicity, is assumed to be filled with vacuum, since the coronal densities are extremely low (< 10^{-14} g/cm^3). The region z > 0 corresponds to the chromospheric and photospheric layers and is filled with a dense material assumed to have a composition typical of the ambient solar atmosphere with the abundances $a_{amb,i}$ relative to H for ^{4}He, C, N, O, Ne, Mg, Al, Si, S, Ca and Fe nuclei given by Asplund et al. [11]. The region z > 0 is divided into 52 layers which correspond to those given by the VAL-C model for the vertical density profile of the chromospheric region [12], plus a layer for the photospheric region with density $\rho = 3.19 \times 10^{-7}$ g/cm^3. The primary accelerated ions precipitate into the chromospheric-photospheric region from a point located in the coronal region very close to the (xy)-plane. We assume the primary accelerated ions to have an impulsive-flare composition with the enhanced abundances $a_{acc,i}$ relative to protons for the ions heavier than α-particles given in [1] and adopt the values 0.1 and 1 respectively for the α/proton and the ^{3}He/α ratios.

3. Spectra of γ-ray nuclear de-excitation lines

We carry on independent simulation for the collisions of each species *i* of primary accelerated ion and the nuclei of the ambient solar atmosphere. In each simulation we inject 10^6 primary accelerated ions with a downward isotropic angular distribution and a power-law energy distribution given by:

$$\frac{dn_i(E)}{dE} = NE^{-\delta} H(E_{max} - E)\, H\,(E - E_{min})\,, \tag{1}$$

where E is the primary accelerated ion kinetic energy per nucleon in the range from E_{min} = 1 MeV to E_{max} = 1 GeV, δ is the spectral-index, H is the Heavyside step-function and N is a constant defined to normalize the power-law energy distribution to one ion:

$$N \int_{E_{min}}^{E_{max}} E^{-\delta} dE = 1\,. \tag{2}$$

The full energy spectrum of photons, in units of photons *per* GeV *per* primary proton in the energy range from E_{min} to E_{max}, is calculated by summing up the contributions from each species i of primary ion weighted by the relative abundances $a_{acc,i}$:

$$\frac{d\Phi(E_{ph})}{dE_{ph}} = \sum_i a_{acc,i} \frac{d\Phi_i(E_{ph})}{dE_{ph}}, \tag{3}$$

where E_{ph} denotes the photon energy. The spectral component produced by the direct reactions is calculated by summing up the contributions from the collisions of primary protons, ^{3}He and α-particles with each species j of ambient nuclei:

$$\frac{d\Phi_{dir}(E_{ph})}{dE_{ph}} = \sum_j f_j \left[\frac{d\Phi_{p,j}(E_{ph})}{dE_{ph}} + a_{acc,\alpha} \frac{d\Phi_{\alpha,j}(E_{ph})}{dE_{ph}}\, a_{acc,^3He} \frac{d\Phi_{^3He,j}(E_{ph})}{dE_{ph}}\right]. \tag{4}$$

The quantity f_j is a correction factor for the number density of the ambient nuclei species j, given by:

$$f_j = a_{amb,j} \frac{A_j}{\langle A\rangle}, \tag{5}$$

where $a_{amb,j}$ and A_j are respectively the relative abundance and mass number of the ambient nuclei species j, and $\langle A\rangle = \sum_j a_{amb,j} A_j$ is the average mass number of the ambient nuclei. The spectral component produced by the inverse reactions is calculated by summing up the contributions from the collisions of primary ions heavier than α-particles with all ambient nuclei:

$$\frac{d\Phi_{inv}(E_{ph})}{dE_{ph}} = \sum_{i\neq p,\alpha,^3He} a_{acc,i} \frac{d\Phi_i(E_{ph})}{dE_{ph}}. \tag{6}$$

In order to obtain the spectra of γ-ray nuclear de-excitation lines we use a set of configuration parameters available in FLUKA to turn off Compton scattering, bremsstrahlung of electrons and positrons, electron-positron annihilation, electron-positron pair production, neutron capture and pion decay. In Figure 2 we show the total spectra of γ-ray nuclear de-excitation lines obtained with FLUKA and with the RMK code for primary ions with power-law energy distribution of spectral index δ = 4. We see a remarkable good agreement between FLUKA and RMK results, particularly for the strong lines from the de-excitation of ^{12}C nuclei at 4.44 MeV and ^{16}O nuclei at 6.13, 6.92 and 7.12 MeV. The discrepancies near the dominant lines below 2 MeV, produced by the de-excitation of ^{16}O nuclei at 0.94 and 1.04 MeV, ^{20}Ne nuclei at 1.63 MeV and ^{28}Si nuclei at 1.78 MeV can be traced to statistical fluctuations in the FLUKA spectrum. One should note that the intensity of the nuclear continuum for energies > 8 MeV is lower in the FLUKA spectrum, reflecting the different treatments of the continuum in FLUKA and RMK. A further detailed investigation is necessary to fully understand this discrepancy.

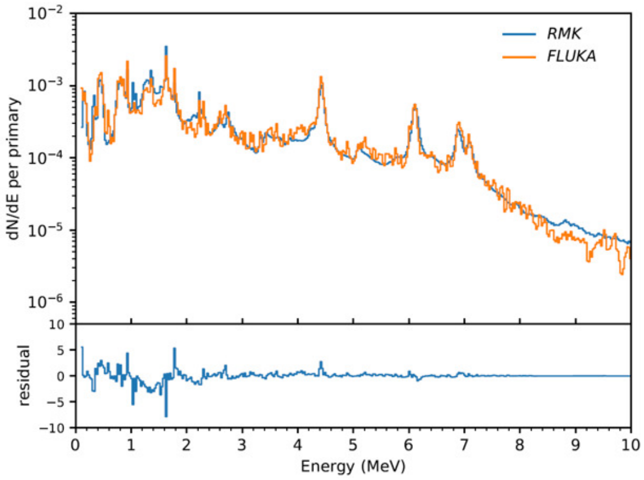

Figure 2. Total spectra of γ-ray nuclear de-excitation lines obtained with FLUKA and the RMK code.

4. Templates

Templates for spectra of γ-ray nuclear de-excitation lines for arbitrary values of the spectral index δ can be synthetized by applying power-law weights to a basic set of photon spectra obtained for primary ions with uniform energy distribution. In Figure 3 we show the results obtained for the total spectra and the spectral components produced by the direct and inverse reactions for $\delta = 2.0$, 3.0, 3.5 and 4.0. We see that the spectra exhibit less statistical fluctuations as the energy distributions become harder.

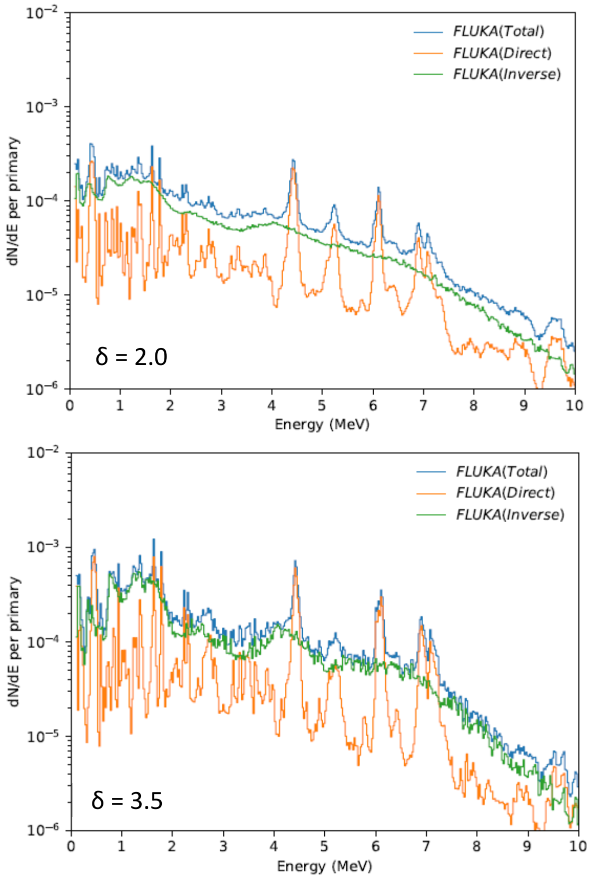

Figure 3. Templates for spectra of γ-ray nuclear de-excitation lines obtained with FLUKA for primary ions with power-law energy distributions of spectral indexes $\delta = 2.0$; 3.0; 3.5; 4.0.

5. Summary and final remarks

We used the Monte Carlo package FLUKA to calculate spectra of γ-ray nuclear de-excitation lines produced by solar flare accelerated ions, considering power-law energy distributions with different spectral indexes. We employed a new simulation strategy that allows to obtain spectra that exhibit reliable statistics and resolution in energy and are in remarkable good agreement with those calculated with the code developed by Murphy et al. [5]. From these model spectra, we build templates that can be used with OSPEX for the analysis and interpretation of γ-ray data from events observed with instruments such as the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT), both on board of the FERMI satellite [13], and the Reuven Ramaty High Energy Spectroscopic Imager (RHESSI) [14].

Acknowledgements

This work was supported by FAPESP (proc. 2017/13282-5). R. M. Thereza acknowledges support from CAPES and Instituto Presbiteriano Mackenzie. C. G. Giménez de Castro acknowledges support from CNPq. P. J. A. Simões acknowledges support from Fundo Mackenzie de Pesquisa.

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