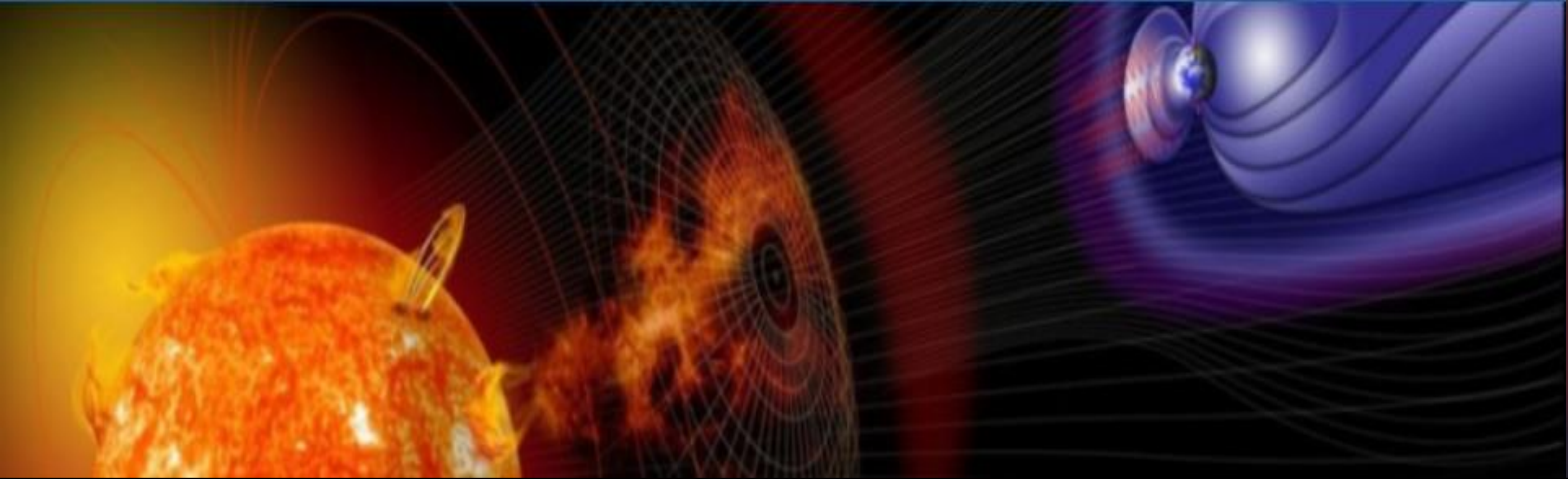

Development of FLUKA Templates for the Modelling of Nuclear De-Excitation Gamma-Ray Line Spectra from Solar Flares

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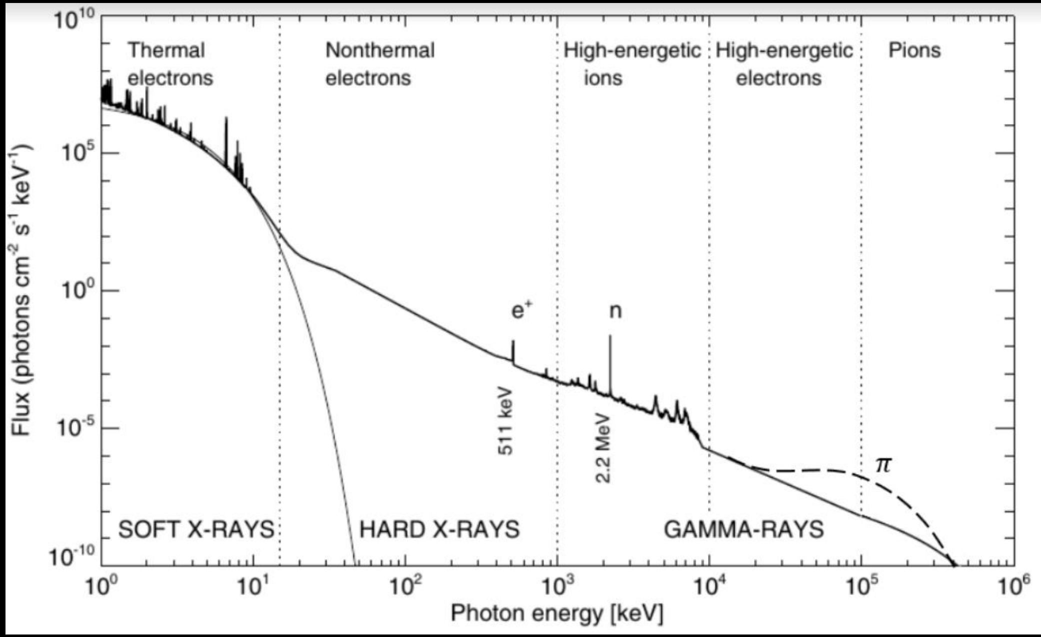
Introduction



Modelling of gamma-ray spectra observed in solar flares

Best-fit of data using a set of independent templates and functions for the several spectral components produced by the relevant physical processes:

- **Bremsstrahlung: power-law functions.**
- **Nuclear de-excitation: Ramaty et al. (1979); Murphy et. al. (2002); Murphy et. al. (2009) – RMK Code.**
- **Neutron capture: Hua et. al. (2002); Pelowitz (2013).**
- **Positron annihilation: Murphy et. al (2005).**
- **Pion-decay: Murphy el. al (1987).**

Introduction

FLUKA: a general-purpose package of integrated routines for simulation of particle transport and interactions in arbitrary materials.

Main features:

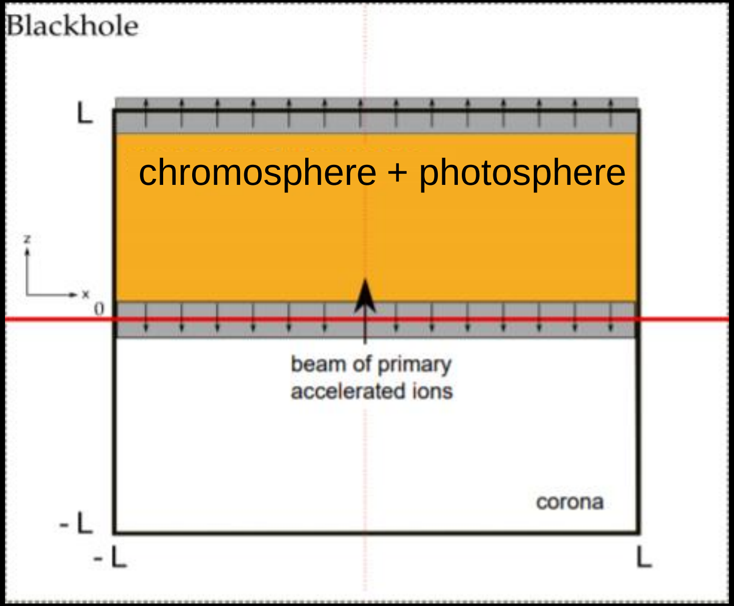
- Accurately simulate the transport and the interactions of about 60 different types of particles (photons, electrons, muons, hadrons, neutrons, neutrinos, etc.)
- Includes robust physics-based models for electromagnetic, hadronic and nuclear interactions which are continuously updated through comparisons with experimental data.

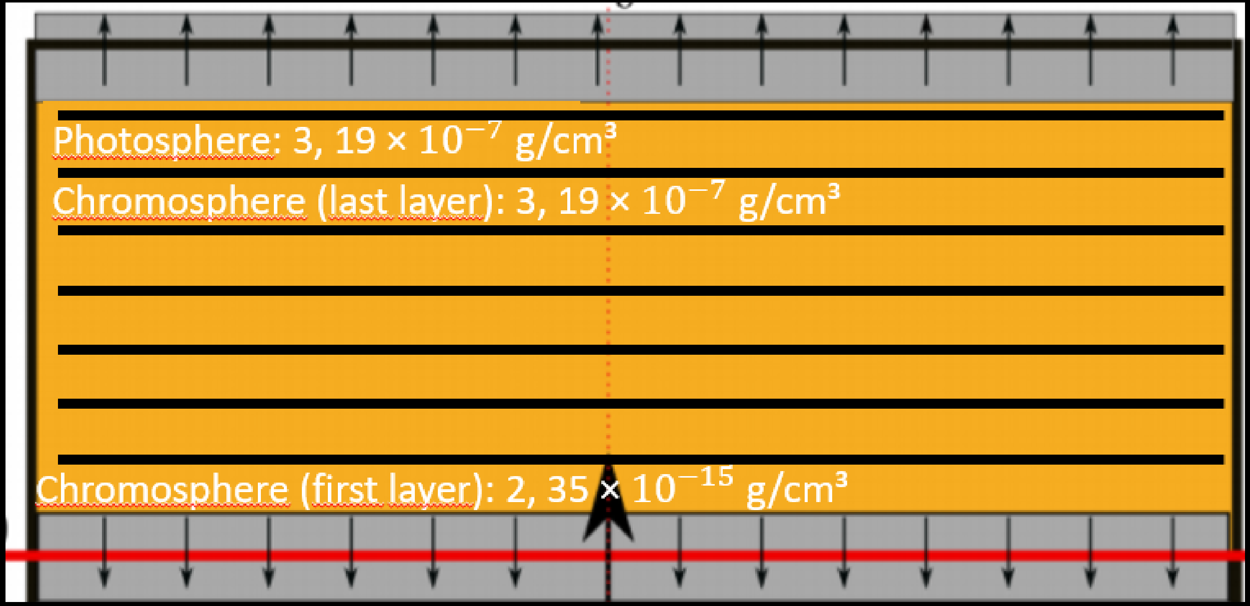
In recent works (Tusnski et al., 2019; MacKinnon et al., 2020), we have demonstrated the potential of the Monte Carlo package FLUKA as an effective tool for the simulation of nuclear processes in the context of solar flares, as well as its capability to implement a self-consistent treatment of the several spectral components in the energy range from 100's keV to 100's MeV.

In this work we use FLUKA to calculate nuclear de-excitation gamma-ray line spectra expected from solar flare accelerated ion distributions.

Solar Flare Model

We assume a simple plane-parallel geometry: cubic box centered at the origin of a Cartesian coordinate system (Ox,Oy,Oz) with edges of length $L = 2\times10^9$ cm and faces perpendicular to the coordinate axes. The z-coordinate corresponds to the vertical depth in the ambient solar atmosphere.

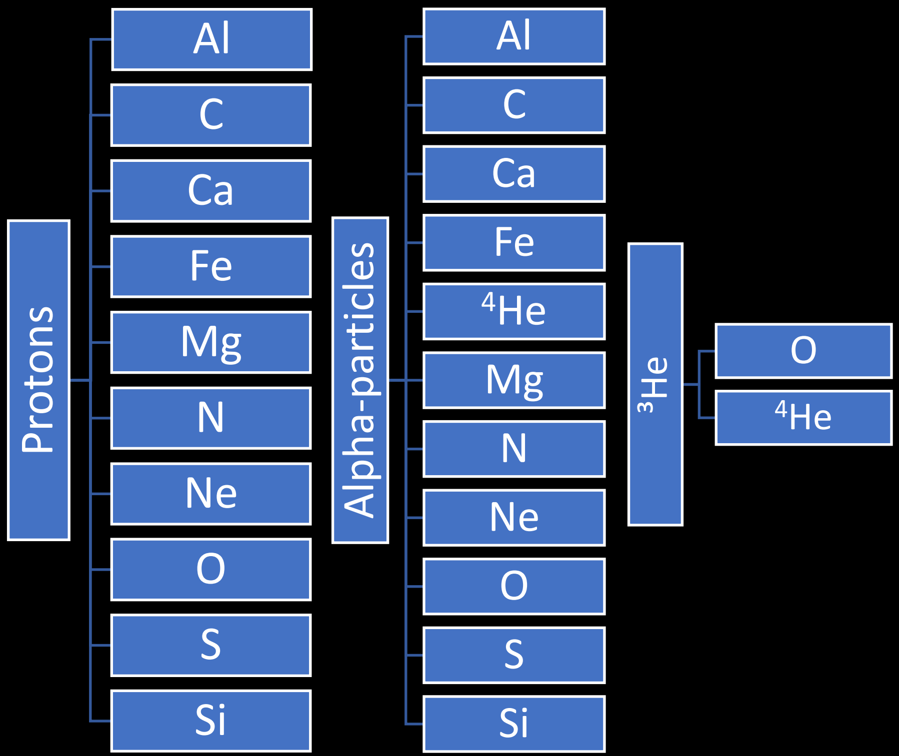




- 52 layers with a vertical density profile given by the VAL-C model of the chromosphere (Vernazza, Avrett, and Loeser, 1981) plus an additional layer corresponding to the photosphere with a density of 3.19×10^{-7} g/cm^3.
- Corona = Vacuum (particles are transported, but do not interact).

Solar Flare Model

Direct Reactions

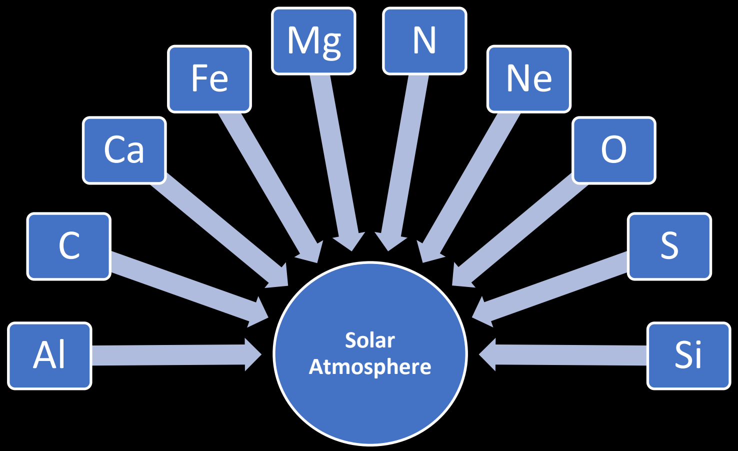


$$\frac{d\phi_{dir}(E_{ph})}{dE_{ph}} = \sum_j f_j \left[\frac{d\phi_{p,j}(E_{ph})}{dE_{ph}} + a_{acc,\alpha} \frac{d\phi_{\alpha,j}(E_{ph})}{dE_{ph}} \right] .$$

$$f_j = a_{amb,j} \frac{n_k^c}{n_{j,k}} = a_{amb,j} \frac{A_j}{\langle A \rangle} .$$

$$\left\langle \frac{dE_k}{dl} \right\rangle = \rho_k \langle g_j(E) \rangle \frac{\sum_j a_{amb,j} Z_j}{\sum_j a_{amb,j} A_j}$$

Inverse Reactions



$$\frac{d\phi_{inv}(E_{ph})}{dE_{ph}} = \sum_{i \neq p,\alpha} a_{acc,i} \frac{d\phi_i(E_{ph})}{dE_{ph}}$$

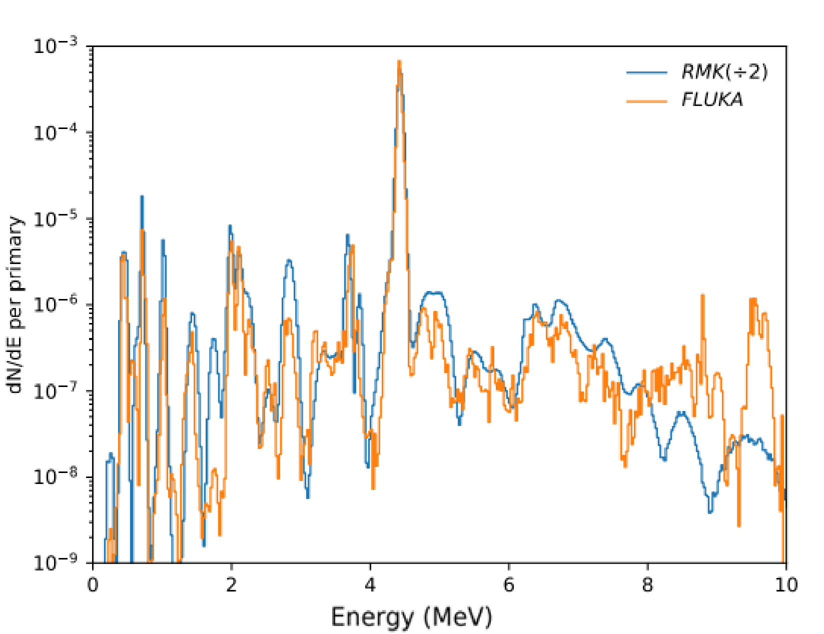
- Solar atmosphere: Asplund et al. (2009)
- Accelerated ions: Murphy et al. (2007)

i	$a_{amb,j}$	$a_{acc,i}$ (impulsive flare)
H	1.0	1.0
^{3}He	–	0.1
^{4}He	8.50×10^{-2}	0.1
C	2.69×10^{-4}	9.30×10^{-4}
N	6.76×10^{-5}	2.48×10^{-4}
O	4.90×10^{-4}	2.00×10^{-3}
Ne	8.51×10^{-5}	9.10×10^{-4}
Mg	3.98×10^{-5}	1.18×10^{-3}
Al	2.82×10^{-6}	3.14×10^{-5}
Si	3.24×10^{-5}	9.10×10^{-4}
S	1.32×10^{-5}	1.91×10^{-4}
Ca	2.19×10^{-6}	2.12×10^{-5}
Fe	3.16×10^{-5}	2.68×10^{-3}

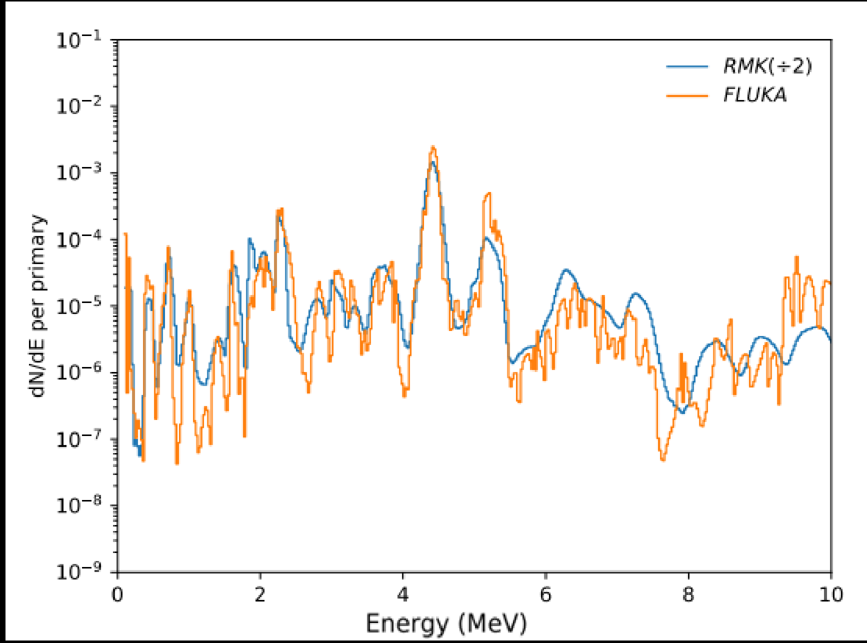
- 10^6 primary accelerated ions.
- Downward isotropic angular distribution;
- Power-law energy distribution with spectral index δ.

Photon Spectra (δ = -4.0)

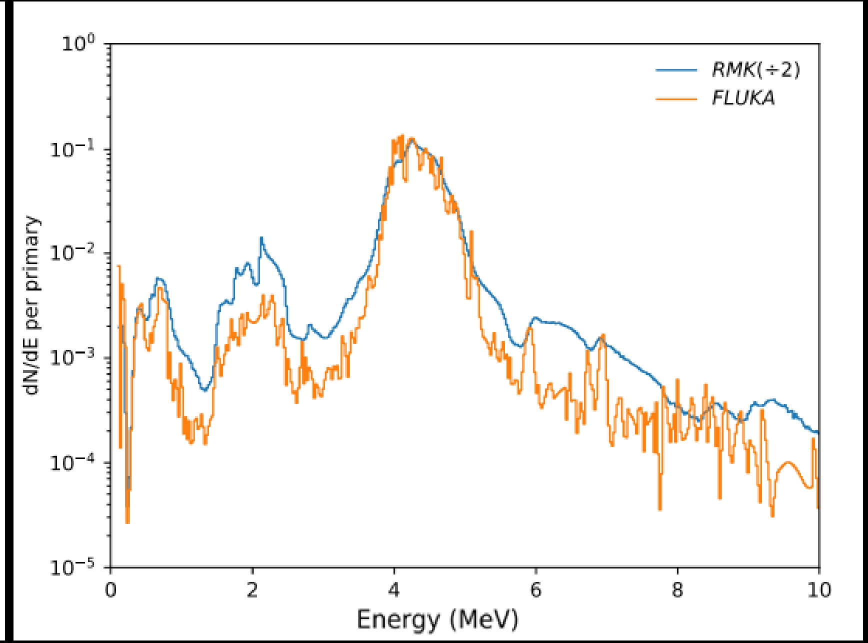
Photon spectra obtained with FLUKA and with the RMK code for primary accelerated protons and alpha-particles injected into a Carbon target and for primary accelerated Carbon ions injected into a target of ambient solar atmosphere composition.



p - C



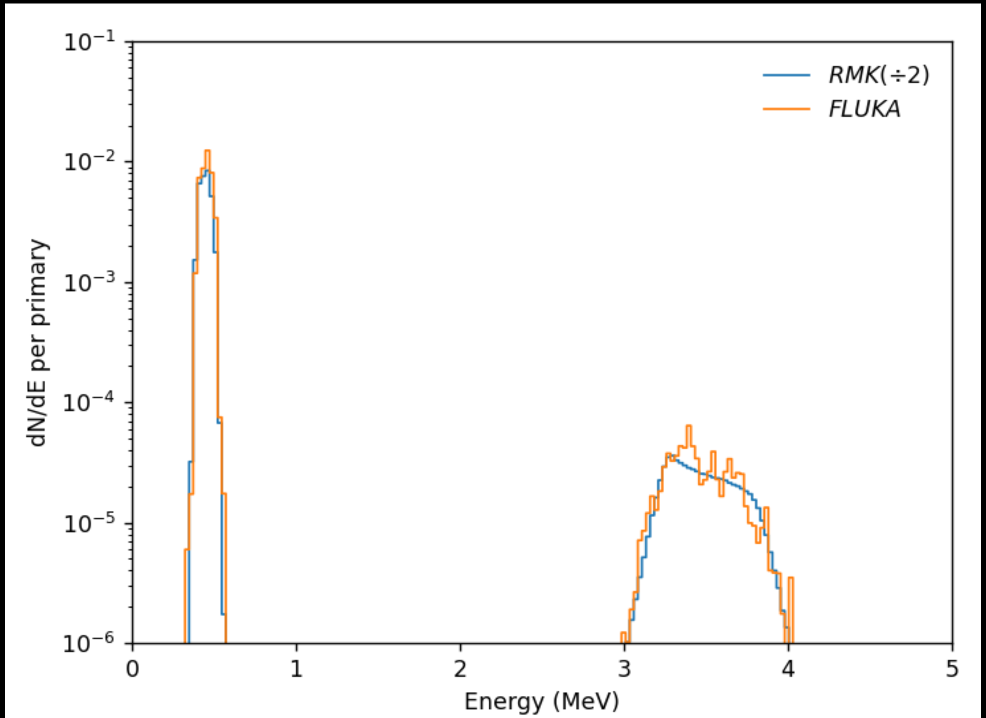
α - C

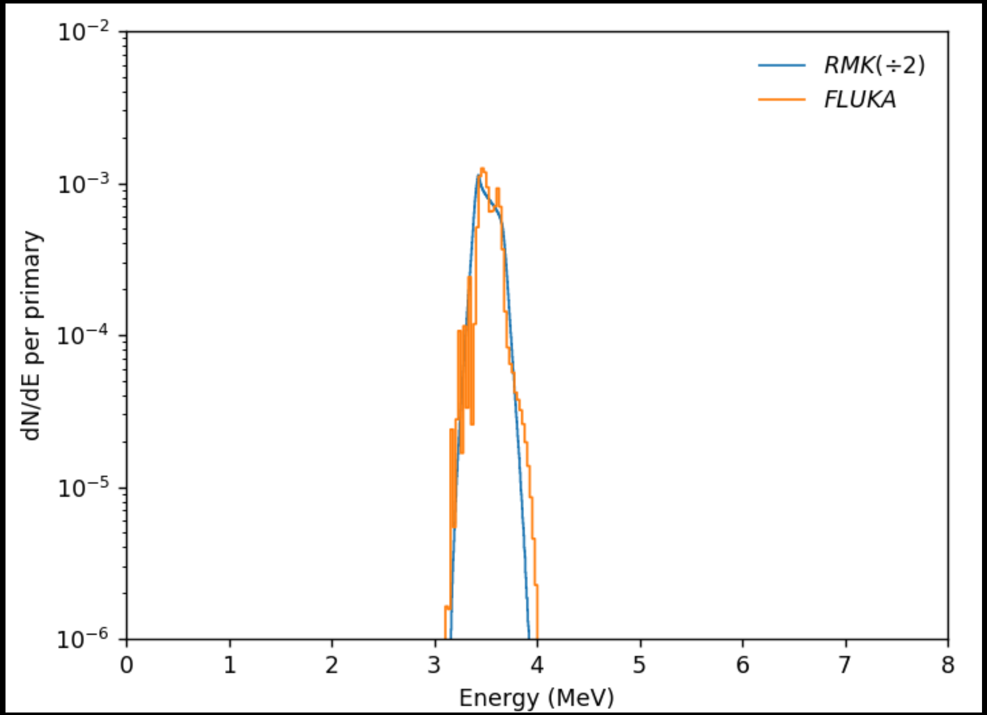


C - amb.

Photon Spectra (δ = -4.0)

Photon spectra obtained with FLUKA and with the RMK code for primary accelerated alpha-particles and ^{3}He ions injected into a Helium target.

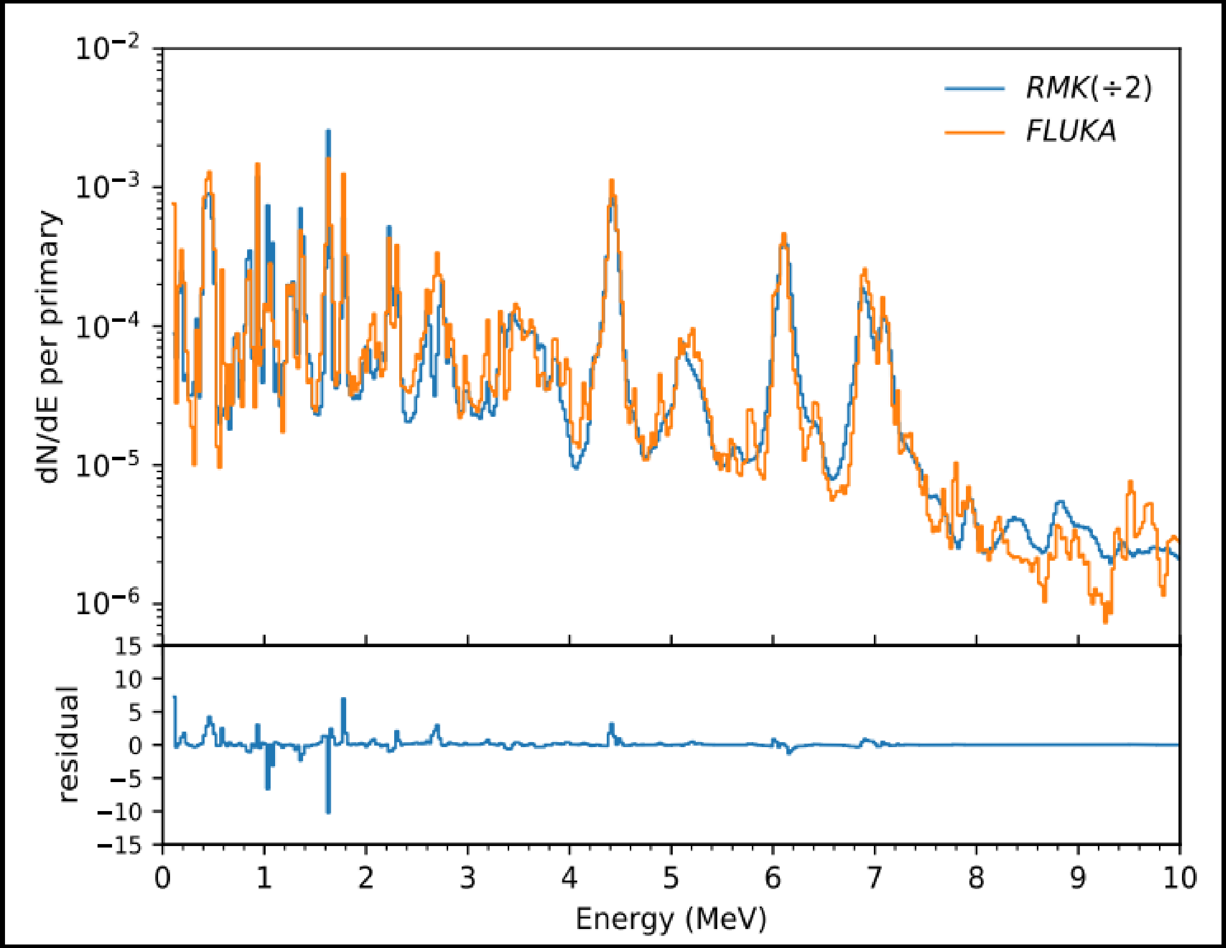




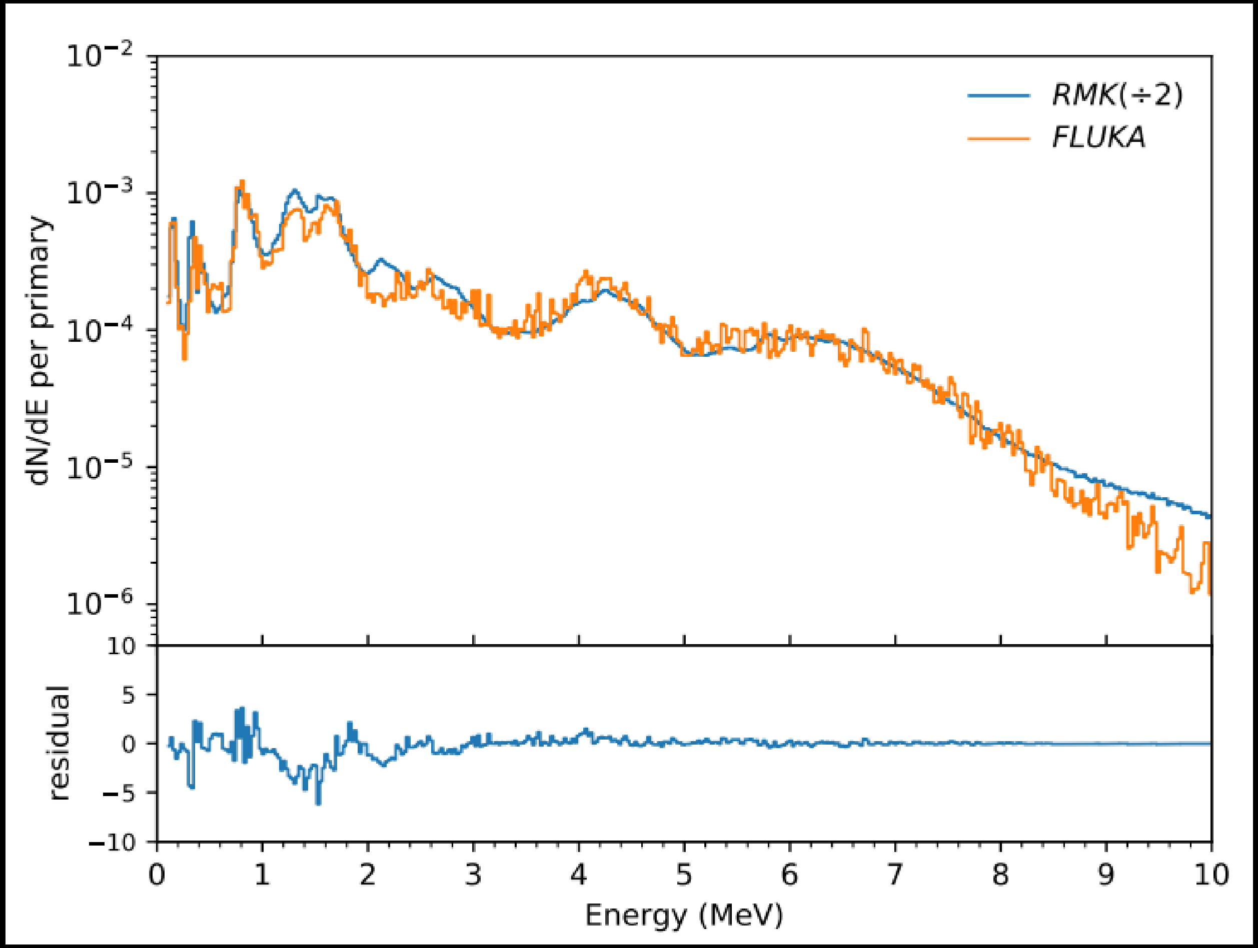
α - ^{4}He

^{3}He - ^{4}He

Photon Spectra (δ = -4.0)

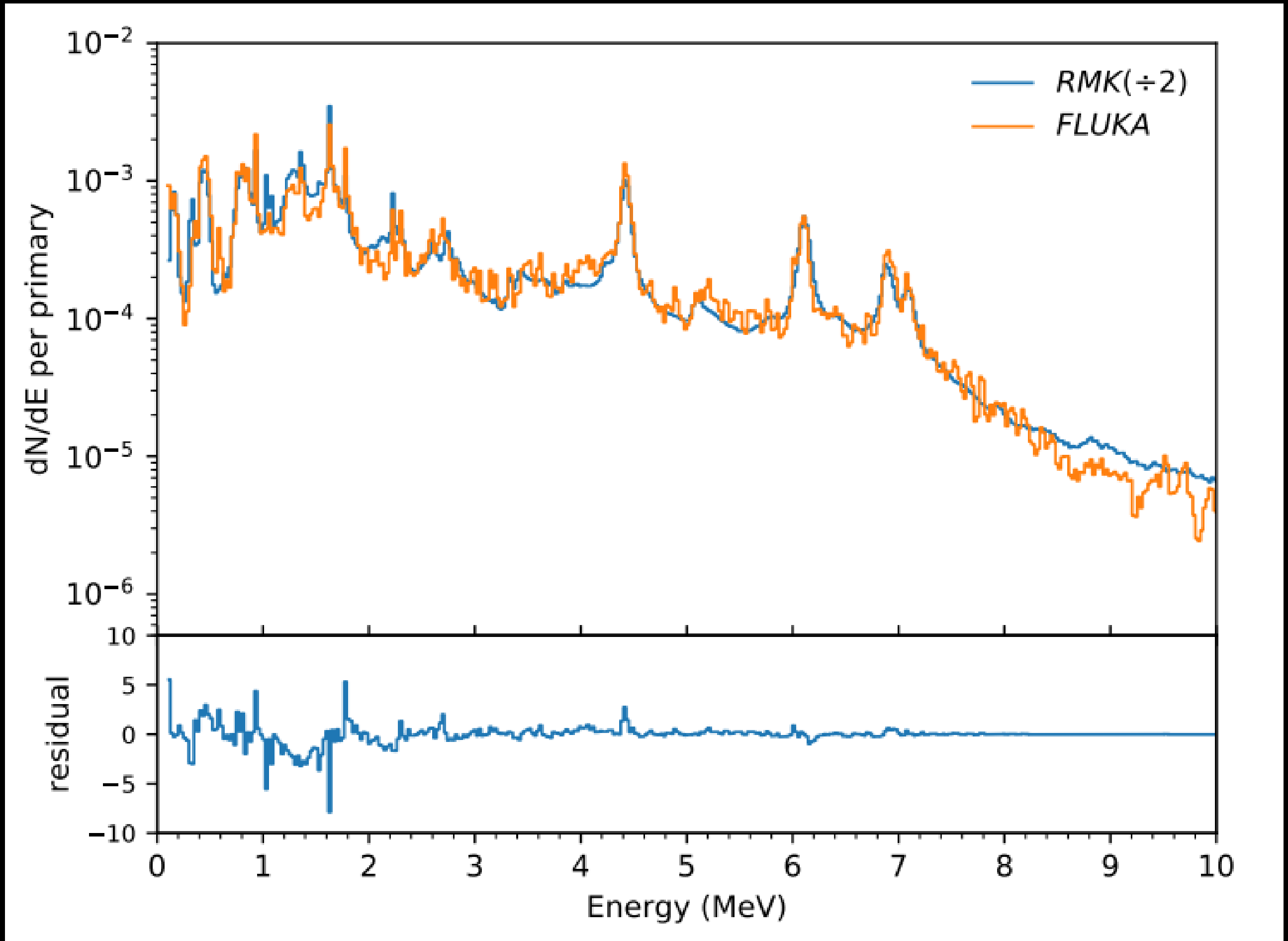


Direct Reactions



Inverse Reactions

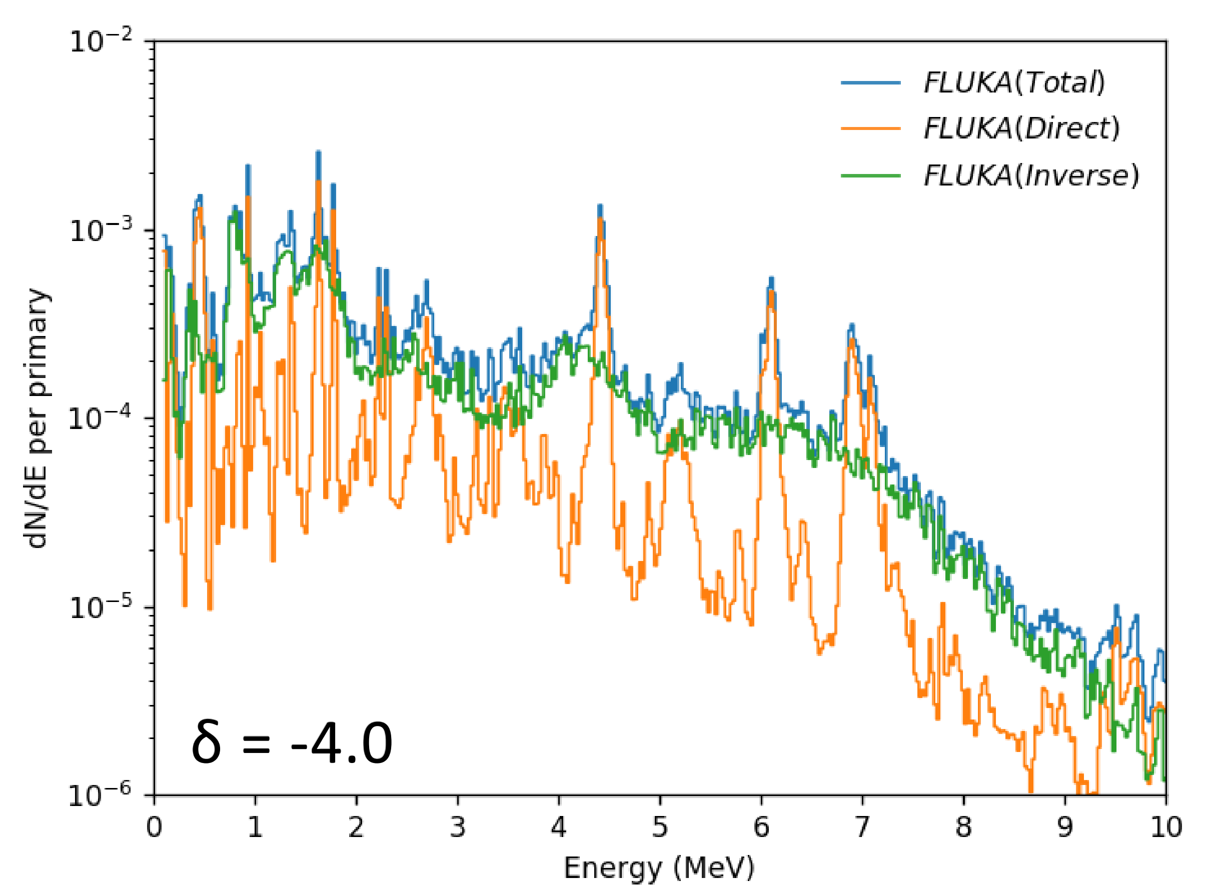
Photon Spectra (δ = -4.0)

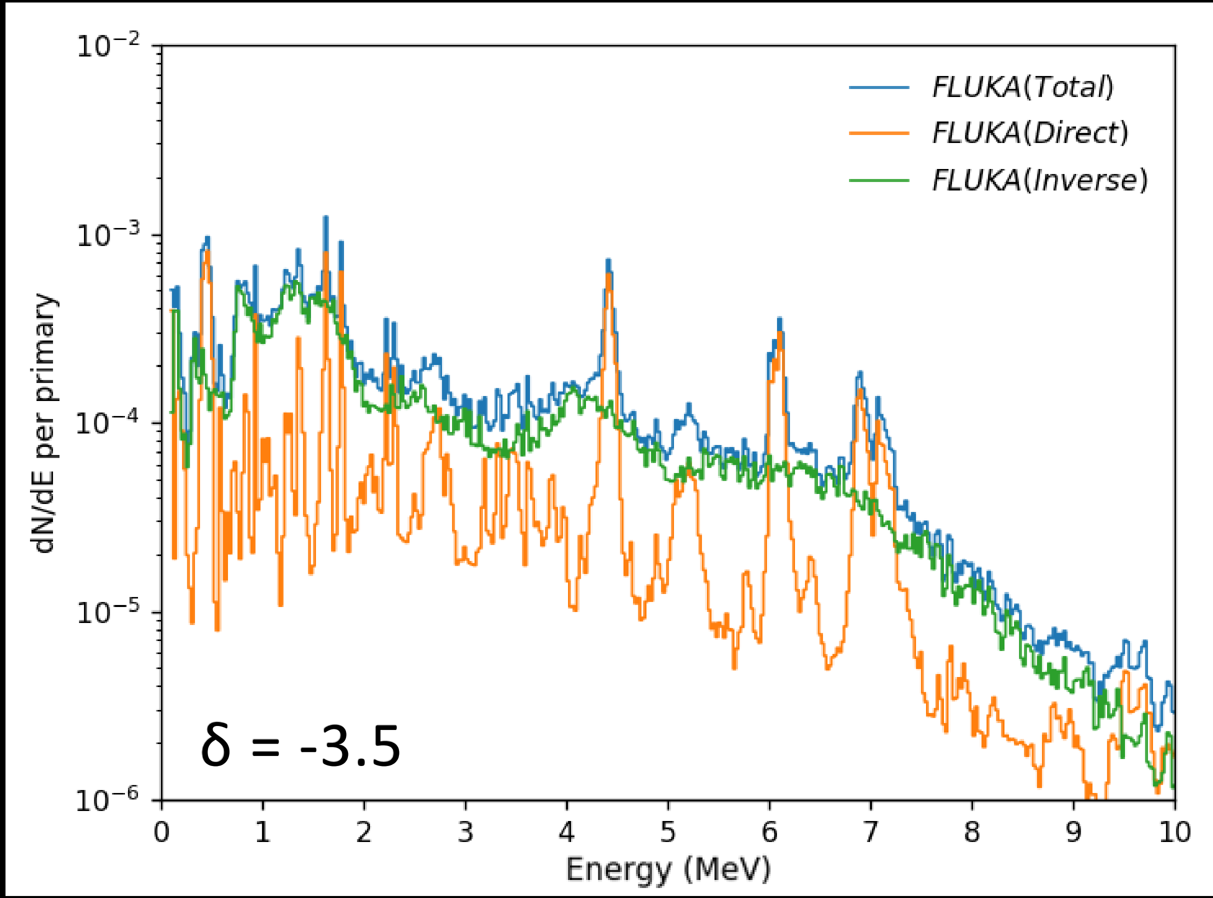


Total Spectrum

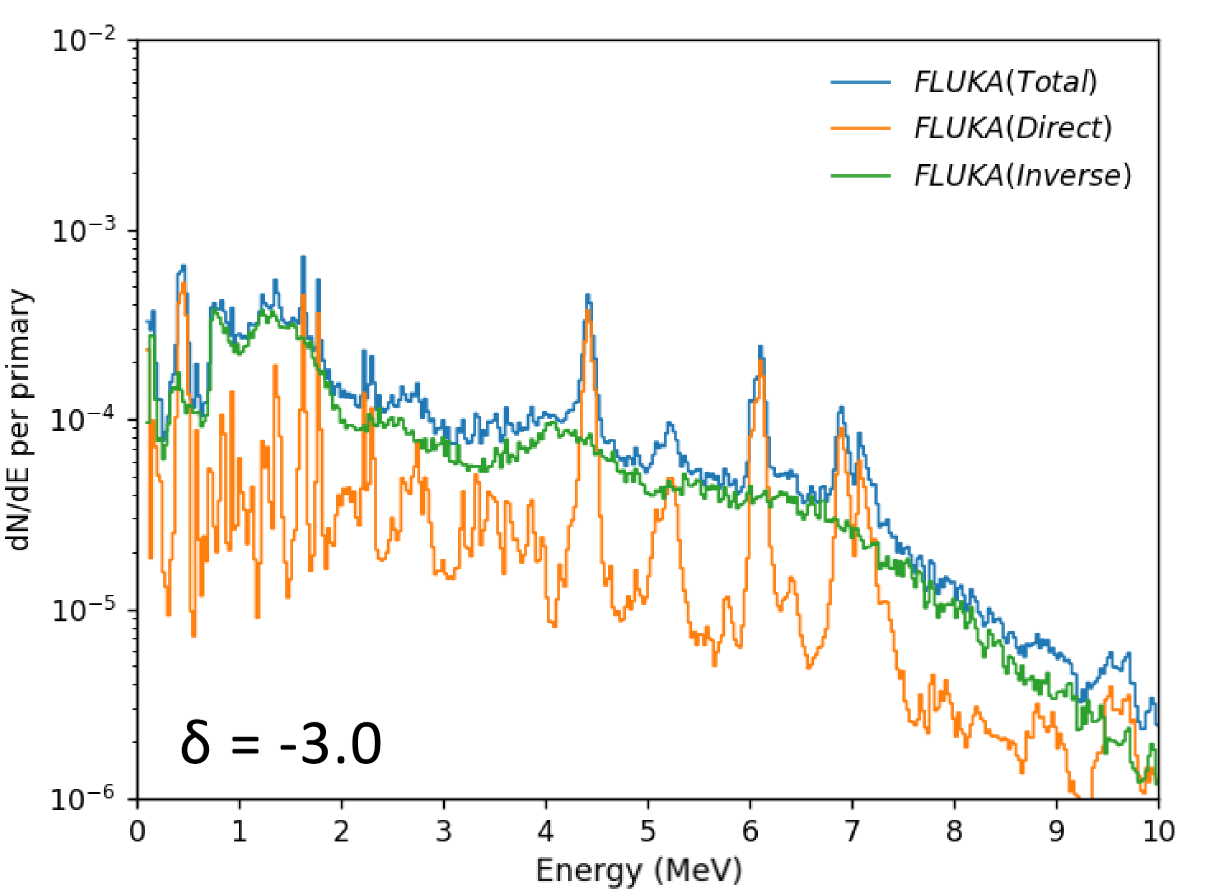
Templates

Nuclear de-excitation gamma-ray line templates for any spectral index δ can be synthetized by applying power-law weights to a basic set of photon spectra obtained from simulations carried out assuming primary accelerated ions with uniform energy distribution.

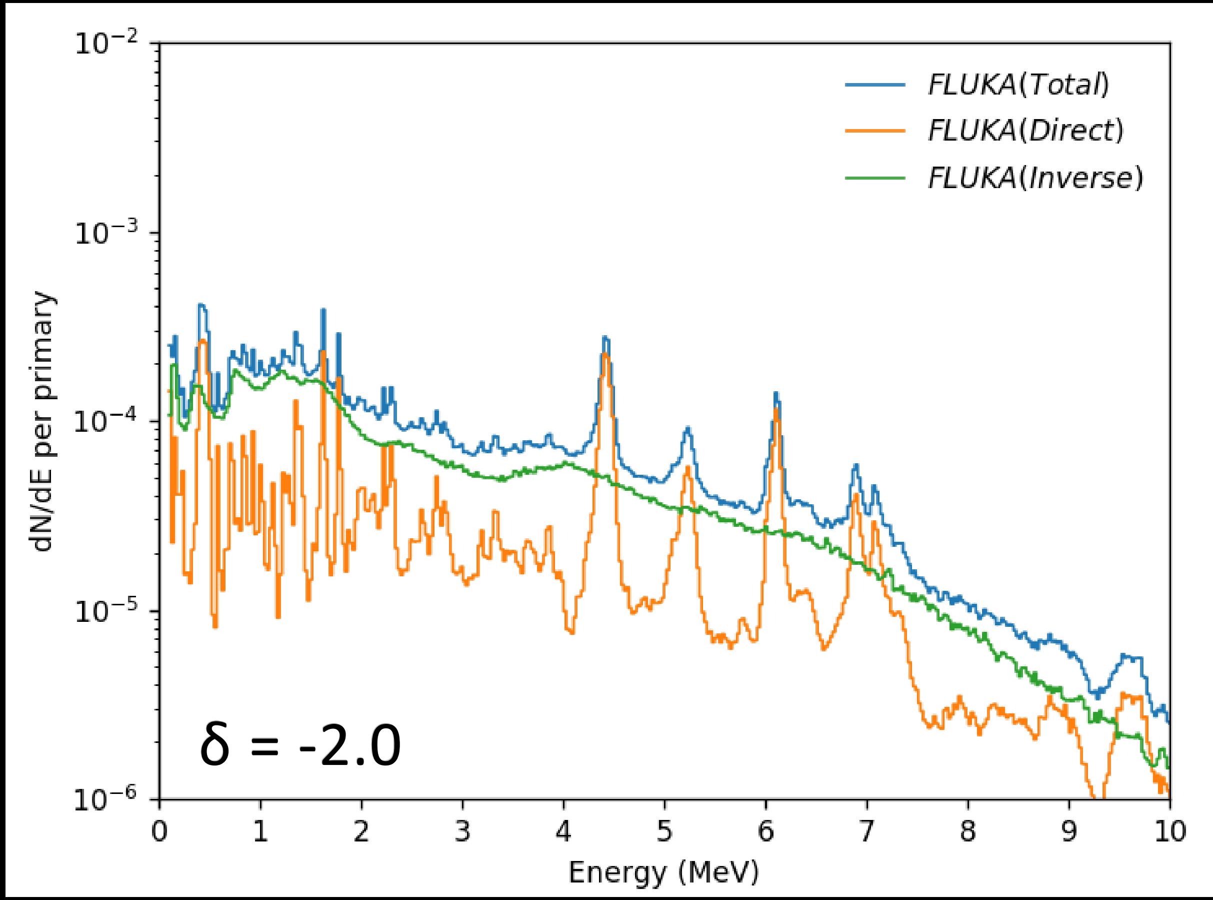




Templates



FLUKA(Total)
FLUKA(Direct)
FLUKA(Inverse)
dN/dE per primary
Energy (MeV)
δ = -3.0



FLUKA(Total)
FLUKA(Direct)
FLUKA(Inverse)
dN/dE per primary
Energy (MeV)
δ = -2.0

Summary

- We show model spectra obtained from a range of assumed primary accelerated ion distributions which exhibit reliable statistics and energy resolution and are in good agreement with those obtained using the code developed by Murphy et al. (2009).
- From these model spectra we build templates which can be incorporated into the software package Objective Spectral Executive (OSPEX) and used in the analysis of solar flare gamma-ray data.