Theoretical study of production of light and intermediate mass fragments from interaction of GCR-LIKE particles

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Introduction

• Galactic cosmic rays are high-energy radiation, originated outside the solar system, composed of 90% protons, 9% $\alpha$-particles, and a small percentage of heavy ions (~1%)

• Because of high charge $\rightarrow$ heavy ions contribute to dose and dose equivalent received in spaceflight ($dE/dX \sim MZ^2$)

• As NASA’s future plans include extended human mission in deep space, these exposures take priority

• Detailed understanding of transport of these heavy ions through matter is needed, as crew will be inside shielded spacecraft, or in habitats.
Introduction (cont.)

• Fragmentation cross sections play a key role in:
  • transport calculations
  • Estimates of dose and dose equivalent

• Accurate and precise database of nuclear reaction cross sections is needed to modelers for both code development and validation purposes

• The purpose of this work is to validate nuclear physics models, used in shielding design and dose calculations, against available experimental data and other models.
Experimental data

• Zeitlin et al. reported fragmentation cross sections measured for $^{16}\text{O}$ beam at 600MeV/u incident on targets of H, C, and Al, and other targets [Physical Review C 83, 34909 (2011)]

• We investigated the fragmentation cross sections for H, C and Al targets. Why?
  • H and C $\rightarrow$ Soft Tissue
  • Al $\rightarrow$ Spacecraft walls
Schematic of space radiation protection problem

GCR Flux for selected nuclei at Solar Minimum (Created by CREME96)
Nuclear Interaction Mechanism

• Interaction of projectile with target nucleus is divided into:
  1. Dynamical stage $\rightarrow$ highly excited fragments are formed through direct reactions and pre-equilibrium reactions
  2. Statistical stage $\rightarrow$ highly excited fragments lose their excitation energies by emission of light particles and $\gamma$-rays and finally reach their ground states
1. **SAPTON**: Scattering And Production Theory of Nuclei: modified statistical model with final state interaction

2. **Geant4**: Geometry and tracking 4: is a toolkit for simulations of the passage of particles through matter:
   a) G4-INCLXX: Updated version of the intranuclear cascade model (INCL++) that can handle heavy-ion collisions.
   b) G4-Shielding: Based on Bertini model, and Quantum-Molecular-Dynamics (QMD) model.
SAPTON

- SAPTON is a modified version of the standard statistical model.
- It has a final-state interaction between the emitted fragments.
- It distinguishes itself from other models in at least one important aspect:
  
  *It includes the possibility that the fragments are being emitted in the ground states, excited states, as well as in the continuum.*

- Double differential cross-section for the production of a pair of fragments $A_1$ and $A_2$ is given by

$$
\frac{d^2\sigma}{d\Omega dE} \propto \int \frac{T_1(\varepsilon)\rho_1(U_1)\rho_2(U_2)}{\rho_c(U_c)} dU_1 dU_2
$$

where

- $T_1(\varepsilon)$ is the transmission Coefficient between the pair with relative energy $\varepsilon$
- $\rho_1, \rho_2$ are their level densities
- $U_1, U_2$ are their excitation energies
- $\rho_c, U_c$ are the level density and excitation energy of the composite system
• $T_l(\varepsilon)$ represents the final-state interaction between the fragments in the exit channel

• It is calculated from a realistic complex optical potential

$$T_l(\varepsilon) = 1 - |S_l|^2$$

• The existence of such potential governs the dynamics of the fragmentation process entirely by dividing it into various reaction channels according to various relative angular momentum $l$-values (which are related to the impact parameter)

• This allows fragments to be emitted in ground, excited states, as well as in the continuum $\rightarrow$ fragments might be unstable while detected (similar to fission-like process)
600 MeV/u $^{16}$O + $^{27}$Al

\[ \sigma_Z (\text{mb}) \]

- Zeitlin et al.
- SAPTON
- G4INCLXX
- G4SHEILDING

Charge Z

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Conclusions

• SAPTON shows better agreement with data → statistical stage dominates

• Both G4-INCLXX and G4-Shielding overestimate production cross sections of $Z \leq 2$, while underestimate that of $Z = 4$ → dynamical stage dominates.

• Fragments cross sections increase with target mass for SAPTON (consistent to data), but not for Geant4 models → dynamical stage vs. statistical stage

Thank You! Questions?