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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% α-particles, and a small percentage of heavy ions (~ 1%)
- Because of high charge → 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

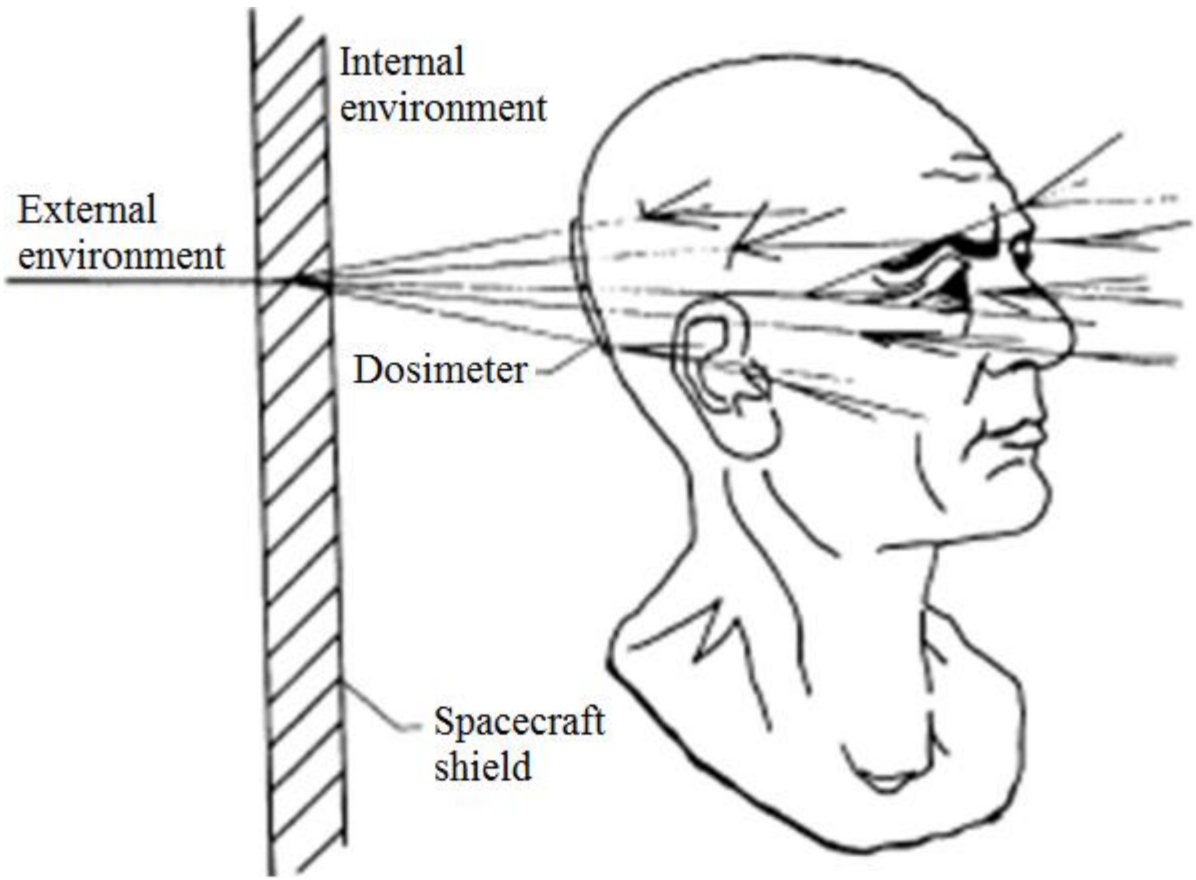
- **The purpose of this work is to validate nuclear physics models, used in shielding design and dose calculations, against available experimental data and other models.**

Experimental data

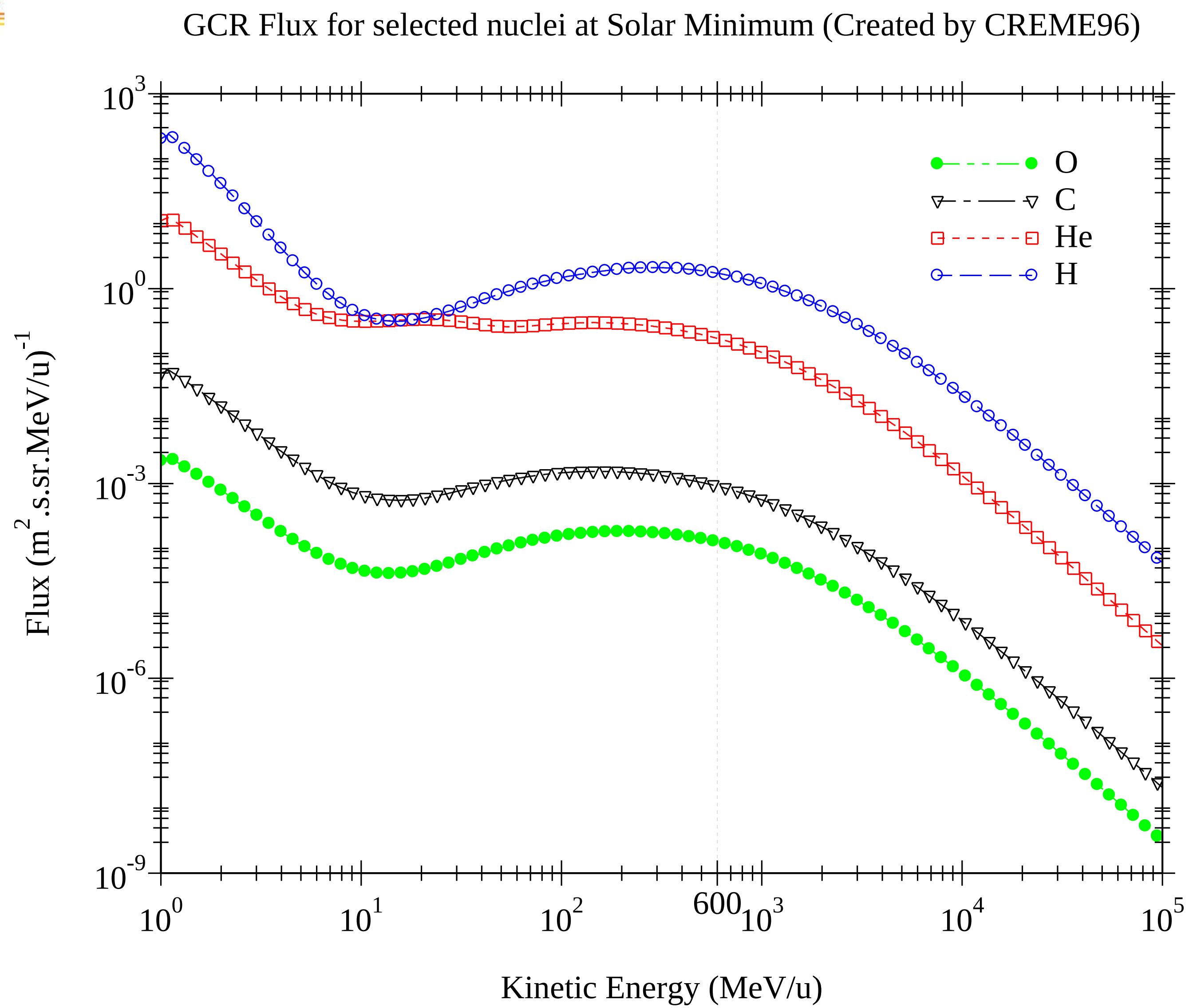
- Zeitlin *et al.* reported fragmentation cross sections measured for ^{16}O beam at 600MeV/u incident on targets of H, C, and Al, and other targets [***Physical Review C 83, 34909 (2011)***]

- We investigated the fragmentation cross sections for H, C and Al targets. Why?
  - H and C → Soft Tissue
  - Al → Spacecraft walls

Schematic of space radiation protection problem

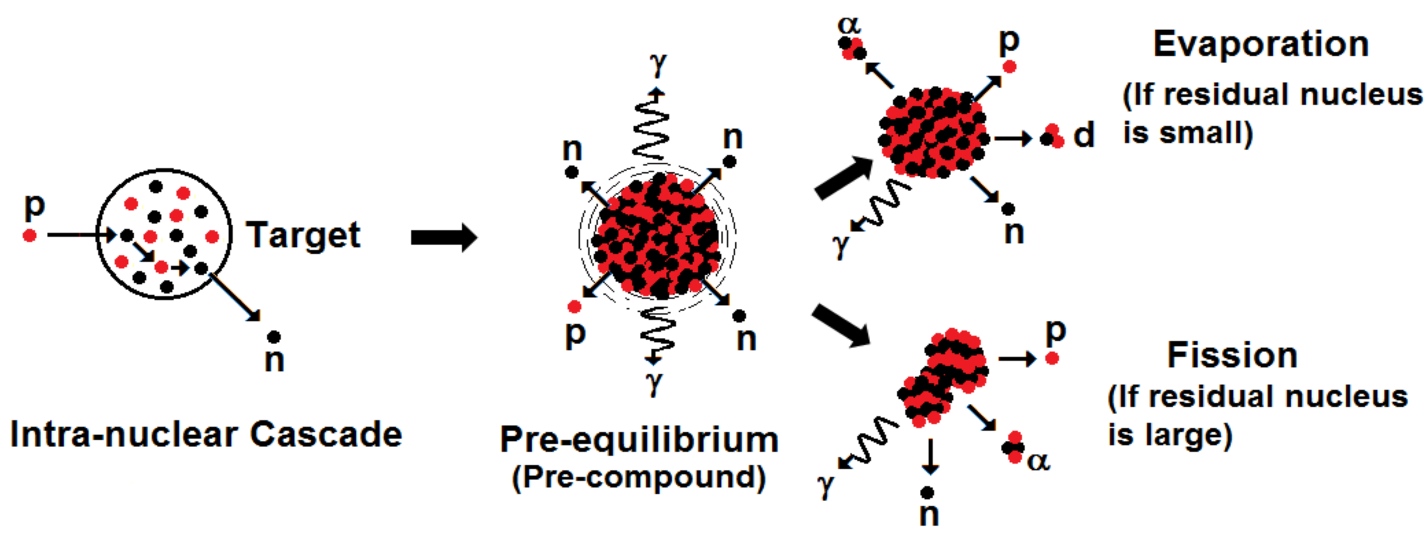


- From Wilson *et al.*, NASA Reference Publications 1257 (1991)


GCR Flux for selected nuclei at Solar Minimum (Created by CREME96)
O
C
He
H
Flux (m^2.s.sr.MeV/u)$^{-1}$
10^3
10^0
10^{-3}
10^{-6}
10^{-9}
10^0
10^1
10^2
600
10^3
10^4
10^5
Kinetic Energy (MeV/u)

Nuclear Interaction Mechanism

- Interaction of projectile with target nucleus is divided into:
  1. Dynamical stage → highly excited fragments are formed through direct reactions and pre-equilibrium reactions
  2. Statistical stage → highly excited fragments lose their excitation energies by emission of light particles and γ–rays and finally reach their ground states



Nuclear Models

1. **SAPTON**: **S**cattering **A**nd **P**roduction **T**heory of **N**uclei : modified statistical model with final state interaction

2. **Geant4**: **Ge**ometry **an**d **t**racking 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 $\boldsymbol{A}_1$ and $\boldsymbol{A}_2$ is given by

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

where

- $T_l(\varepsilon)$ is the transmission Coefficient between the pair with relative energy ε
- ρ_1, ρ_2 are their level densities
- U_1, U_2 are their excitation energies
- ρ_c , U_c are the level density and excitation energy of the composite system

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SAPTON

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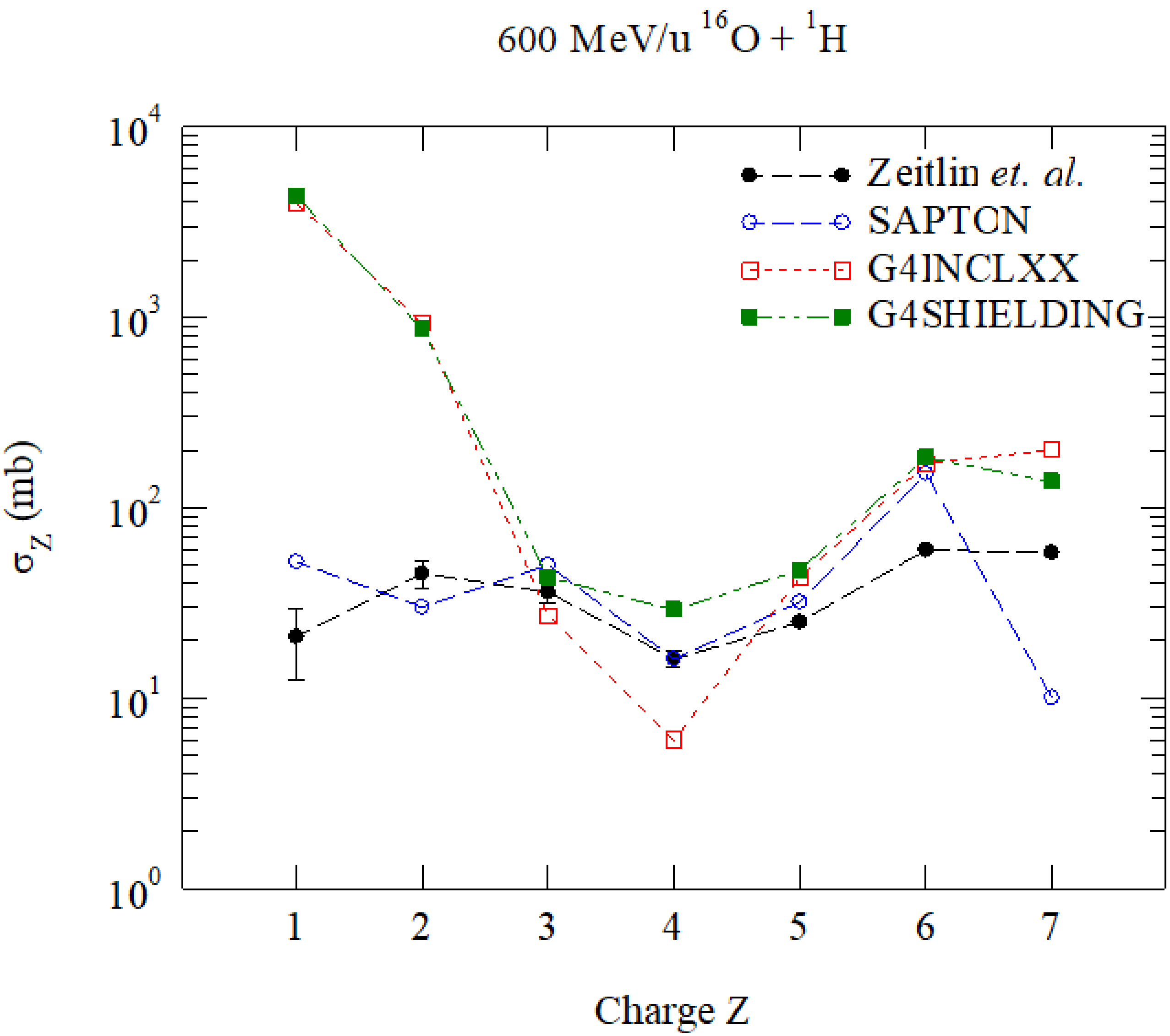
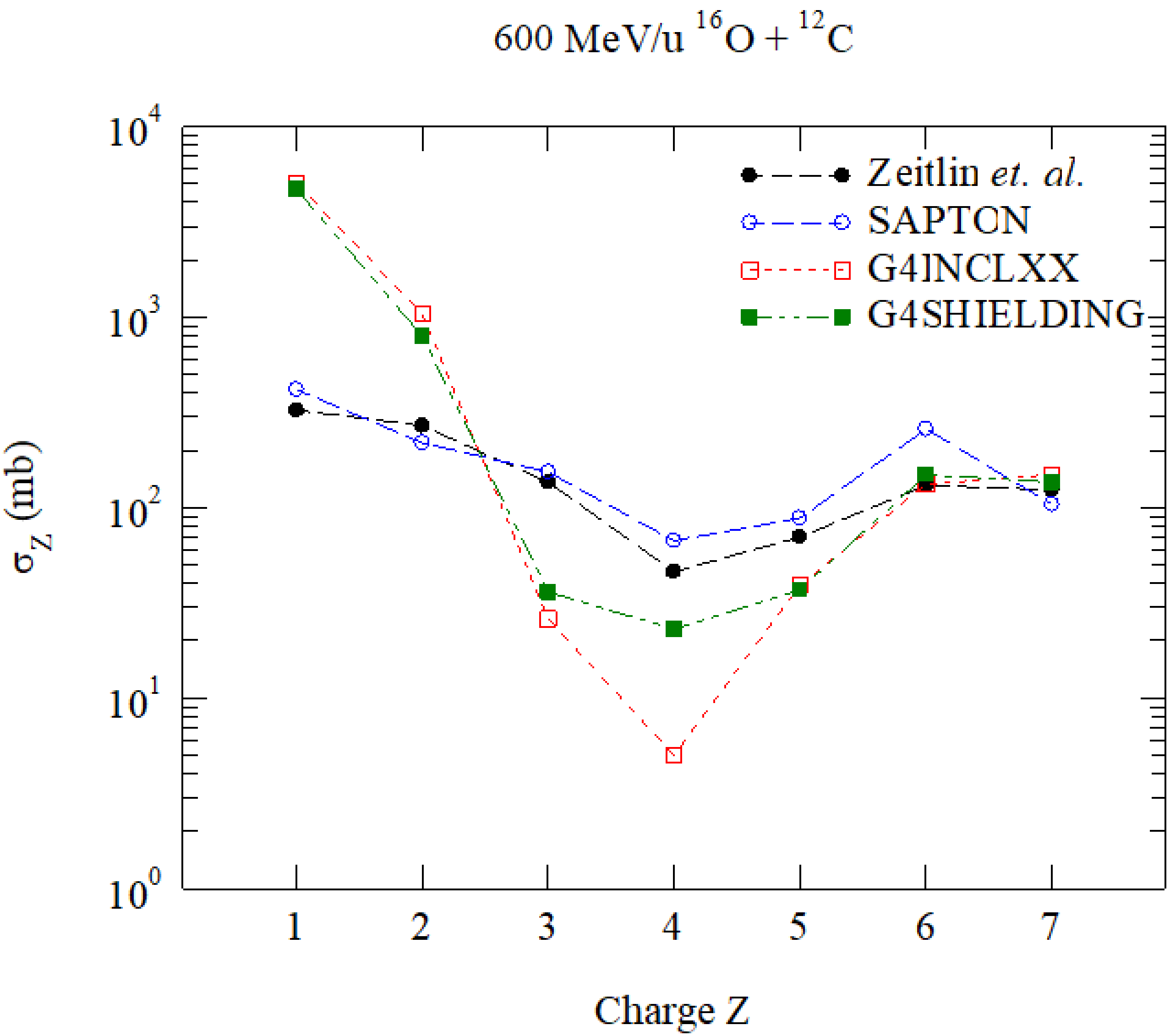
- $T_l(\varepsilon)$ represents the final-state interaction between the fragments in the exit channel
- It is calculated from a realistic complex optical potential

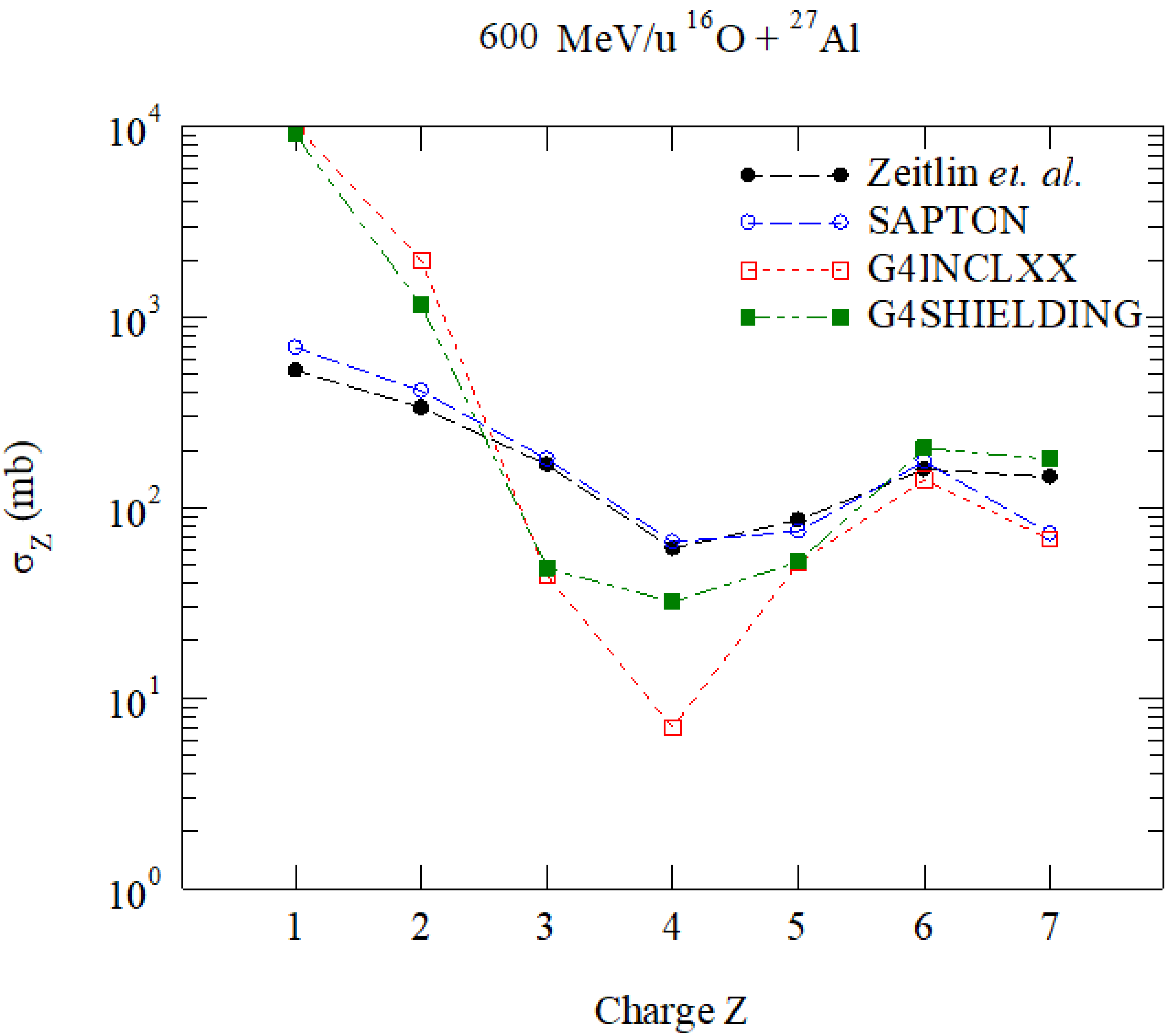
$$T_l(\varepsilon) = 1 - |S_l|^2$$

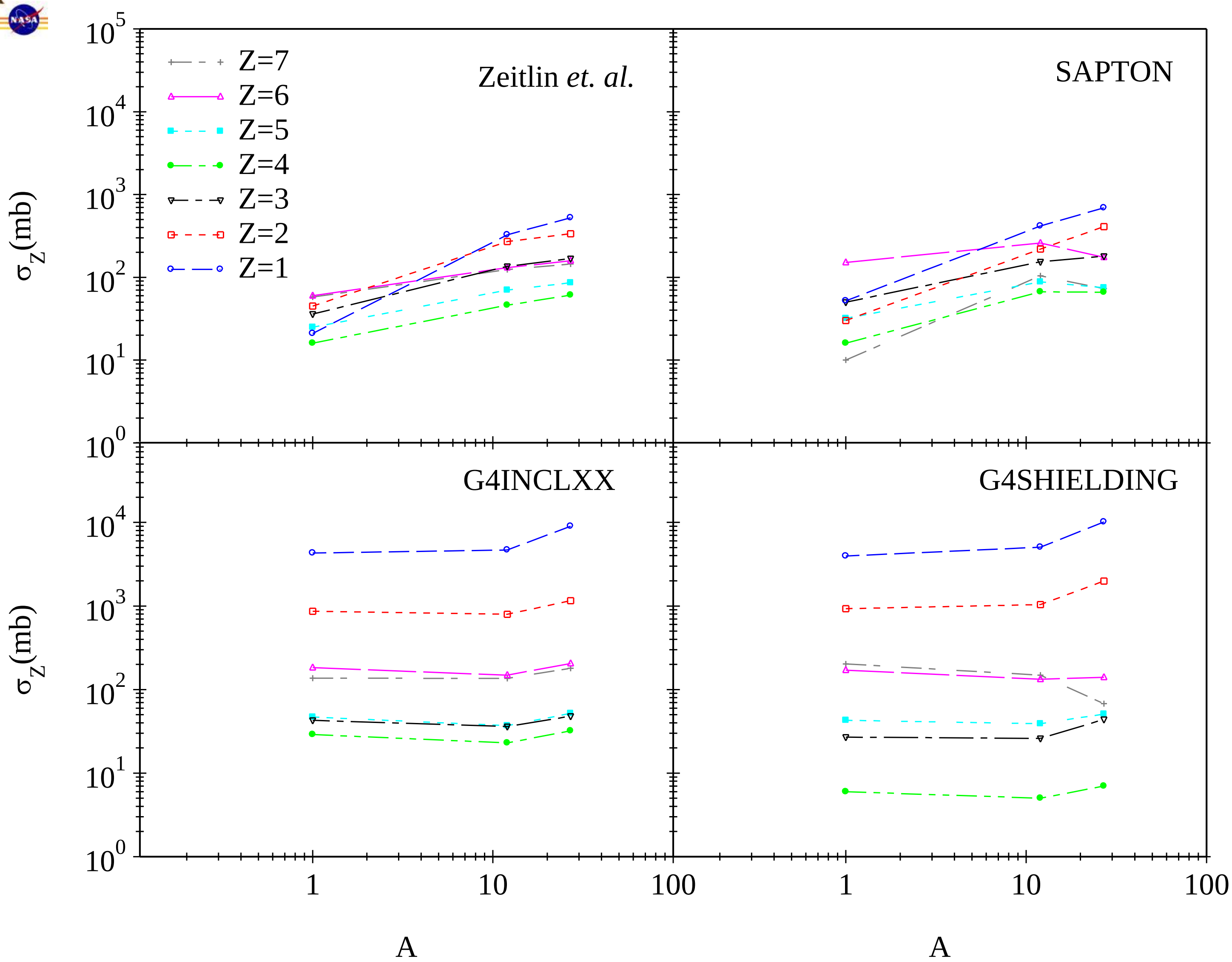
- The existence of such potential governs the dynamics of the fragmentation process entirely by dividing it into various reaction channels according to various relative angular momentum *l*-values (which are related to the impact parameter)
- This allows fragments to be emitted in ground, excited states, as well as in the continuum → fragments might be unstable while detected (similar to fission-like process)


600 MeV/u $^{16}O + ^{1}H$
σ_Z (mb)
Charge Z
Zeitlin *et. al.*
SAPTON
G4INCLXX
G4SHIELDING
10^4
10^3
10^2
10^1
10^0
1
2
3
4
5
6
7



600 MeV/u $^{16}O + ^{12}C$
10^4
10^3
10^2
10^1
10^0
σ_Z (mb)
1
2
3
4
5
6
7
Charge Z
Zeitlin *et. al.*
SAPTON
G4INCLXX
G4SHIELDING


600 MeV/u ^{16}O + ^{27}Al
Zeitlin et. al.
SAPTON
G4INCLXX
G4SHIELDING
σ_Z (mb)
Charge Z
10^4
10^3
10^2
10^1
10^0
1
2
3
4
5
6
7


Zeitlin et. al.
SAPTON
G4INCLXX
G4SHIELDING
Z=7
Z=6
Z=5
Z=4
Z=3
Z=2
Z=1
σ_Z(mb)
A

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?