Cross Section Calculations and Comparison to Experiment

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Outline

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• Abrasion Stage Formalism
• Ablation Stage Formalism
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Introduction

• Incident heavy charged particles from galactic cosmic rays and solar energetic particle events undergo nuclear collisions as they pass through spacecraft structures, shielding, and astronauts’ bodies.

• Many of these nuclear collisions result in breakup of the nuclei of heavier incident particles, as well as the nuclei of the target atoms they encounter.

• Accurate estimates of biological risk requires knowledge of the composition (primaries and their collision products – secondaries) within the propagating radiation fields.

• Therefore, nuclear breakup models are needed to accurately estimate the propagating radiation fields.
Abrasion-Ablation Fragmentation Model

$t \sim 0 \text{ sec}$

$P_i \rightarrow T \rightarrow T \rightarrow P_i^*$

ABRASION
Abrasion-Ablation Fragmentation Model

$P_i \rightarrow T \rightarrow T \rightarrow P_i^*$

$t \sim 10^{-22}$ sec

excited prefragment

abraded nucleons

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Abrasion-Ablation Fragmentation Model

\[ t \sim 10^{-16} \text{ sec} \]

\[ P_i \rightarrow T \rightarrow T \]

\[ P_i^* \rightarrow \text{Alpha} \rightarrow \text{Proton} \rightarrow \text{He-3} \]

\[ \text{Deuteron} \rightarrow \text{Neutron} \]

ABLATION
Abrasion-Ablation Fragmentation Model

\[ \sigma_{\text{abr}}(n) \rightarrow \text{Charge Dispersion} \]
\[ \sigma_{\text{abr}}(Z_{PF}, A_{PF}) \rightarrow \text{Excitation Energy (LDM+FSI)} \]
\[ \sigma_{\text{abr}}(Z_{PF}, A_{PF}, E^*) \rightarrow \text{Ablation Model} (\alpha_{ij}) \]

\[ \sigma_F(Z_F) = \Sigma_F \sigma_F(Z_P, A_F) \]

\[ \sigma_F(Z_i, A_i) = \Sigma_j \alpha_{ij} \sigma_{\text{abr}}(Z_j, A_j, E^*) \]
Abrasion Stage Formalism

• The abrasion cross section can be expressed as

\[
\sigma_{abr}(Z_{PF}, A_{PF}) = \left( \frac{N}{N} \right) \left( \frac{Z}{Z} \right) 2\pi \int \left[ 1 - \exp \left( -\frac{2\text{Im} \chi(\vec{b})}{A_p} \right) \right]^{N+Z} \left( \exp \left( -\frac{2\text{Im} \chi(\vec{b})}{A_p} \right) \right)^{A_p-N-Z} 
\]

• The nucleon non-removal probability is

\[
P(\vec{b}) = \exp \left( -\frac{2\text{Im} \chi(\vec{b})}{A_p} \right)
\]

• Thus the probability of a nucleon being removed due to abrasion is

\[1 - P(\vec{b})\]
Abrasion Stage Formalism

• The phase function in above equations is expressed in the eikonal approximation as

\[ \chi(\vec{b}) = -\frac{m}{2k} \int_{-\infty}^{\infty} V(\vec{r}) dz \]

• \( V \) is the optical potential obtained from non-relativistic quantum multiple scattering theory, \( k \) is the wave number, and \( m \) is the nucleon rest mass.
Ablation Stage Formalism

Weisskopf–Ewing Formalism

\[ P_j(\epsilon) d\epsilon = \gamma_j \sigma_j^{\text{cap}}(\epsilon) \frac{W_d(E^*_d)}{W_p(E^*_p)} \epsilon d\epsilon \]

\[ \gamma_j = \frac{g_j m_j}{\pi \hbar^2} \]

\[ P_j(\epsilon) d\epsilon = \text{Probability of Emitting Particle } j \]

\[ \sigma_j^{\text{cap}}(\epsilon) = \text{Capture Cross Section} \]

\[ W_{p/d}(E^*_p) = \text{Level Density of Parent/Daughter Nucleus} \]

\[ g_j = 2s_j + 1 \]
Ablation Stage Formalism

Weisskopf–Ewing Formalism

\[ \Gamma_j = \text{Emission Width of Particle } j \]
\[ \Gamma_{tot} = \text{Total Emission Width} \]
\[ G_j = \frac{\Gamma_j}{\Gamma_{tot}} \]
\[ \Gamma_{tot} = \sum_j \Gamma_j \]
Ablation Stage Formalism
EVA-4 Code

- Cascade + Evaporation

- Cascade weighted by prefragment production cross section (user selected switch for # cascades/mb)

- Part of a legacy code dating back to early 1960s (DFF⇒ Isabel⇒...
EVA Legacy & Improvements: Mass Excess Table

- **Legacy**
- **New Mass Excess Table**
  - New Mass Excess Table + Light Ion Residuals
  - New Mass Excess Table + Light Ion Residuals + New Pairing Energies
EVA Legacy & Improvements: Light Ion Residuals

- Legacy
- **New Mass Excess Table**
- **New Mass Excess Table + Light Ion Residuals**
- **New Mass Excess Table + Light Ion Residuals + New Pairing Energies**

Project\(z_a,e\text{(MeV/u)}\): (18,40,792) \hspace{1cm} \text{Target}(z,a): (6,12)
EVA Legacy & Improvements: Pairing Energy

- Legacy
- New Mass Excess Table
- New Mass Excess Table + Light Ion Residuals
- New Mass Excess Table + Light Ion Residuals + New Pairing Energies
Current Status of EVA: Heavy on Light

Projectile\((z,a,e(\text{MeV/u}))\): (26,56,330)  Target\((z,a)\): (1,1)

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Current Status of EVA:
Heavy on Light

Projectile\((z,a,e(\text{MeV/u}))\): (26, 56, 944)  \quad \text{Target}(z,a): (1, 1)

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Current Status of EVA: Heavy on Light

Projectile($z_a,e$ MeV/u): (26, 56, 1615) | Target($z_a$): (1, 1)
Current Status of EVA: Heavy on Light

Projectile(z,a,e(MeV/u)): (26,56,1512) | Target(z,a): (6,12)

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Current Status of EVA: Heavy on Light

Projectile(z,a,e(MeV/u)): (18,40,352)   Target(z,a): (1,1)
Current Status of EVA: Light on Heavy

Projectile\((z,a,e(\text{MeV/u}))\): \((8,16,2100)\)
Target\((z,a)\): \((82,208)\)
Current Status of EVA: Light on Heavy
Current Status of EVA: Light on Heavy

Projectile(z,a,e(MeV/u)): (8,16,290) | Target(z,a): (82,208)
Sensitivity Study: Excitation Energy

- $1.00 \times EXS$
- $1.10 \times EXS$
- $2.00 \times EXS$
Sensitivity Study: Excitation Energy

- $1.00 \times EXS$
- $1.10 \times EXS$
- $2.00 \times EXS$
Sensitivity Study: Excitation Energy

- $1.00 \times \text{EXS}$
- $1.10 \times \text{EXS}$
- $2.00 \times \text{EXS}$
Concluding Remarks

• HZE collisions undergo an abrasion-ablation process

• Many improvements to the code have been made
  • Be-8 production issue resolved
  • Mass Excess Table Updated
  • Light Ion Residual Cutoff removed
  • Pairing Energy Updated

• Current EVA Results are promising
  • More sophisticated model promises more physical results

• Further efforts to explore
  • Excitation Energy
  • Relativistic Abrasion Formalism
  • Coalescence Model Implementation
Questions?
Back-Up Slides
Ablation: Theory & Methodology

Dostrovsky Parameterizations

- Level Density from Fermi Gas Model

\[ W(E^*) = C(A)e^{2\sqrt{a(E^*-\delta)}} \]

- Capture Cross Section

\[ \sigma_j^{cap}(\epsilon) = \alpha_j \left(1 + \frac{\beta_j}{\epsilon}\right) \sigma_j^g \]

\[ \sigma_j^g = \begin{cases} \pi(R_0 A_d^{\frac{1}{3}})^2, & (j = 1, 2), \\ \pi(R_0 A_d^{\frac{1}{3}} + \rho_j)^2, & (3 \leq j \leq 6) \end{cases} \]

\[ \rho_j = 1.2 \text{ fm} \quad R_0 = 1.5 \text{ fm} \]

\[ \beta_n = \frac{2.12 A_p^{-\frac{2}{3}} - .05}{\alpha_n} \text{ MeV} \]

\[ \beta_j = -k_j V_j \]

\[ \alpha_n = .76 + 2.2 A_p^{-\frac{1}{3}} \]

\[ \alpha_j = 1 + c_j \]
Ablation: Theory & Methodology

Choosing the Kinetic Energy

\[ x_{\text{max}} = a_j^{-1} \left( \sqrt{a_j \tilde{R}_j + \frac{1}{4} - \frac{1}{2}} \right) \]

\[ \tilde{R}_j = \begin{cases} R_n + \beta_n, & \text{neutrons.} \\ R_j, & \text{charged particles.} \end{cases} \]

\[ \epsilon = \begin{cases} x, & \text{neutrons} \\ x + k_j V_j, & \text{charged particles} \end{cases} \]

\[ P_{\text{code}}(x) = \frac{x + \beta_n}{x_{\text{max}}} e^{-2(a_j x_{\text{max}} - \sqrt{a_j (\tilde{R}_j - (x + \beta_n))})} \]