Cross Section Calculations and Comparison to Experiment

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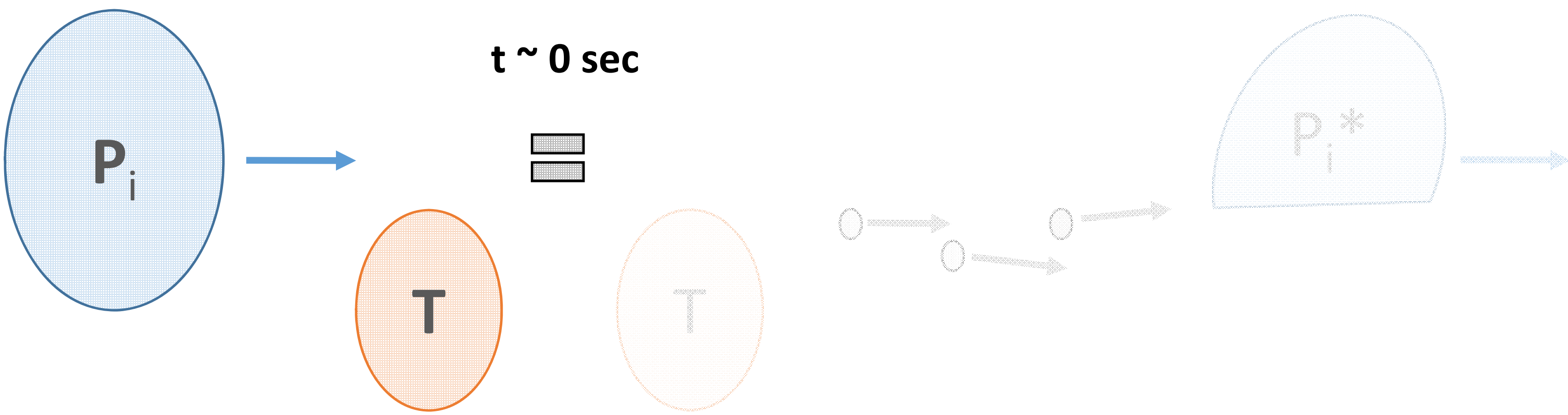
Outline

- Introduction
- Abrasion – Ablation Fragmentation Model
- Abrasion Stage Formalism
- Ablation Stage Formalism
- Updates/Modifications to EVA
- Sample Cross Section Results
- Concluding Remarks

Introduction

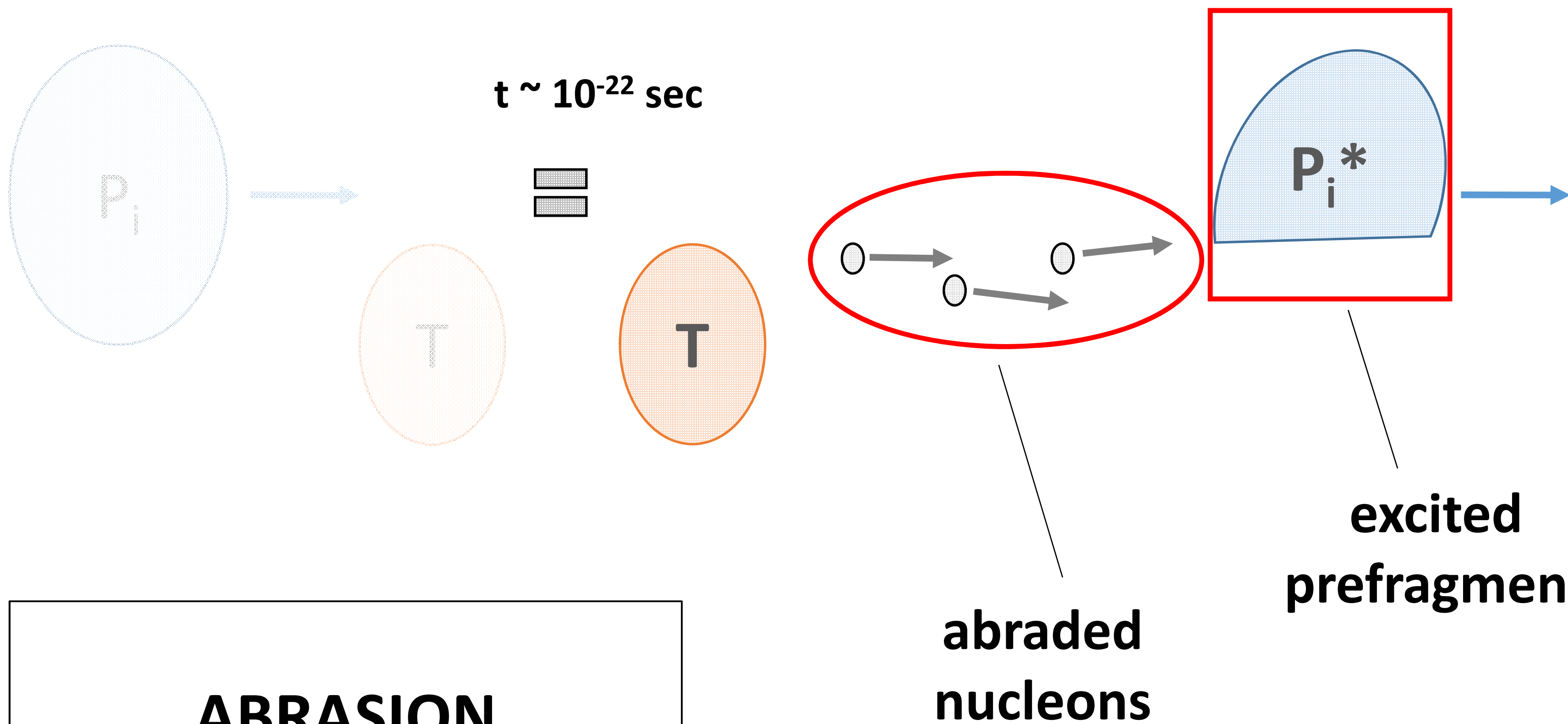
- **Incident heavy charged particles from galactic cosmic rays and solar energetic particle events undergo nuclear collisions as they pass through spacecraft structures, shielding, and astronauts' bodies.**
- **Many of these nuclear collisions result in breakup of the nuclei of heavier incident particles, 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



ABRASION

Abrasion-Ablation Fragmentation Model



ABRASION

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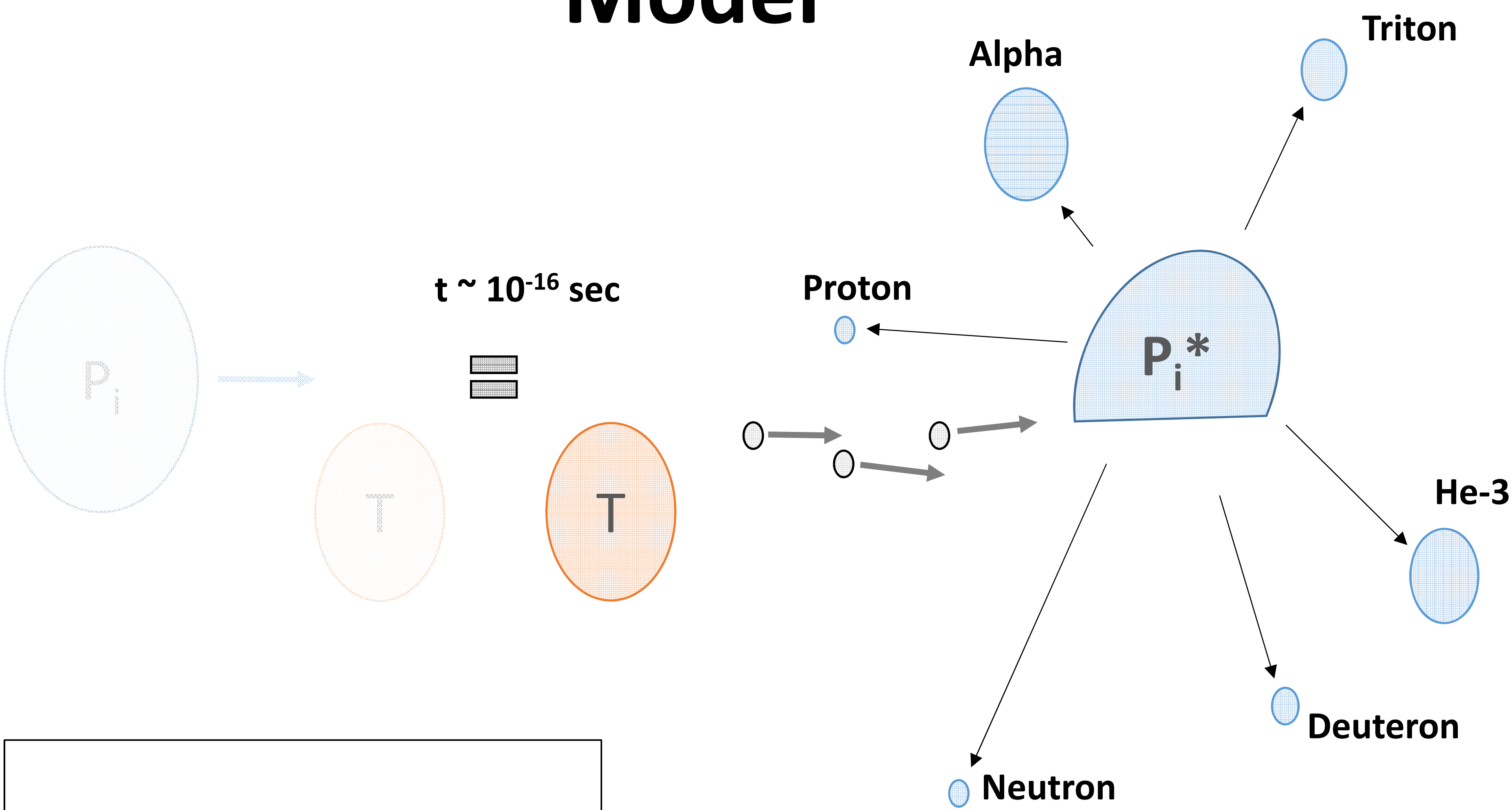
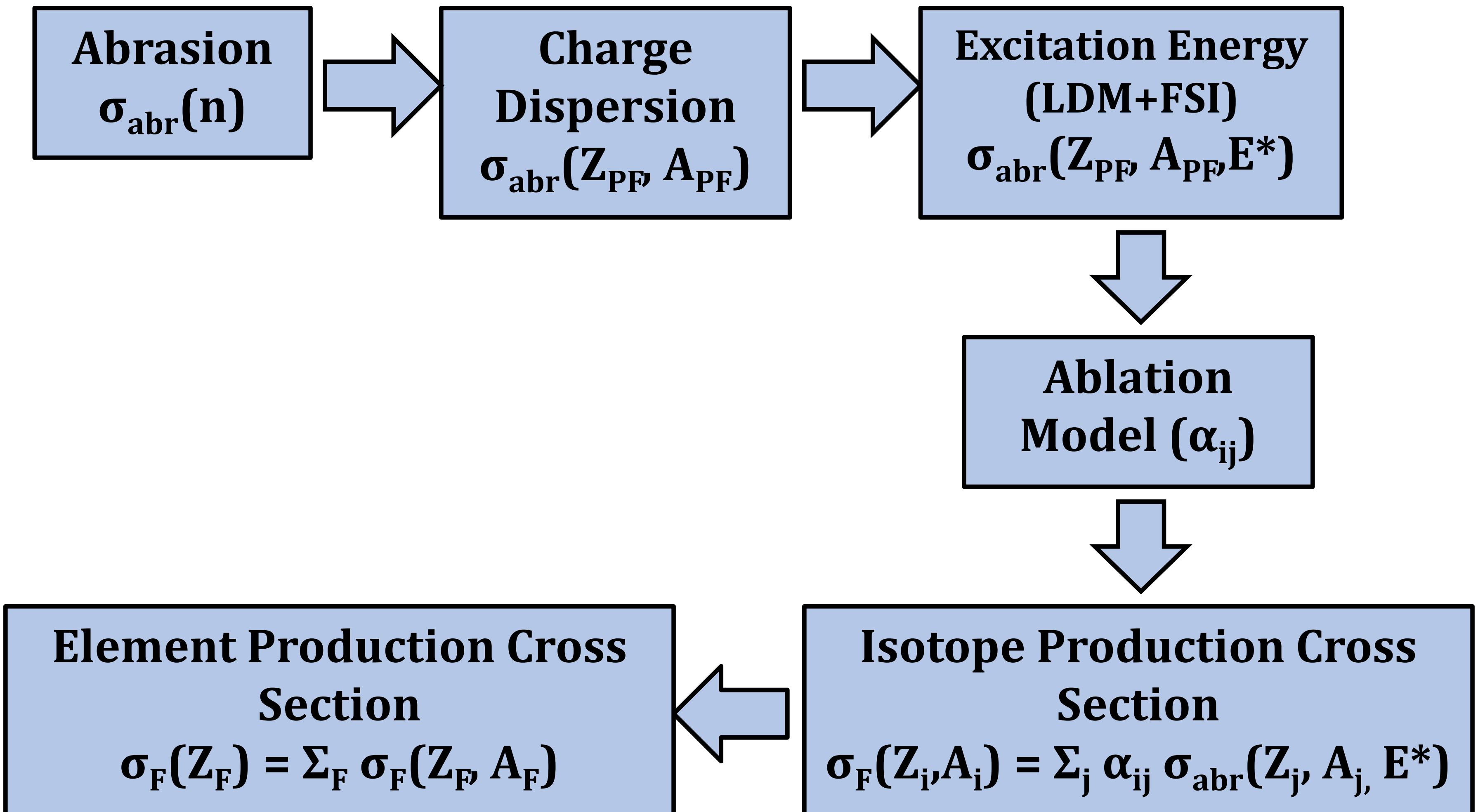


ABLATION

Abrasion-Ablation Fragmentation Model



Abrasion Stage Formalism

- The abrasion cross section can be expressed as

$$\sigma_{abr}(Z_{PF}, A_{PF}) = \binom{N_P}{N}\binom{Z_P}{Z} 2\pi \int \left[1 - \exp\left[\frac{-2\,\mathrm{Im}\,\chi\left(\vec{b}\right)}{A_P} \right] \right]^{N+Z} \left(\exp\left[\frac{-2\,\mathrm{Im}\,\chi\left(\vec{b}\right)}{A_P} \right] \right)^{A_P - N - Z} bdb$$

- The nucleon <u>non-removal</u> probability is

$$P\left(\vec{b}\right) = \exp\left[\frac{-2\,\mathrm{Im}\,\chi\left(\vec{b}\right)}{A_P} \right]$$

- 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

$$P_j(\epsilon)d\epsilon = \gamma_j \sigma_j^{cap}(\epsilon)\frac{W_d(E_d^*)}{W_p(E_p^*)}\epsilon d\epsilon$$

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

$P_j(\epsilon)d\epsilon$ **= Probability of Emitting Particle j**

$g_j = 2s_j + 1$

$\sigma_j^{cap}(\epsilon)$ **= Capture Cross Section**

$W_{p/d}(E^*)$ **= Level Density of Parent/Daughter Nucleus**

Ablation Stage Formalism

Weisskopf–Ewing Formalism

$$\Gamma_j = \int_{\epsilon_{min}}^{\epsilon_{max}} P_j(\epsilon)d\epsilon$$

Γ_j = Emission Width of Particle j

Γ_{tot} = Total Emission Width

$$G_j = \frac{\Gamma_j}{\Gamma_{tot}} \qquad \Gamma_{tot} = \sum_j \Gamma_j$$

G_j = Probability to Emit Particle j

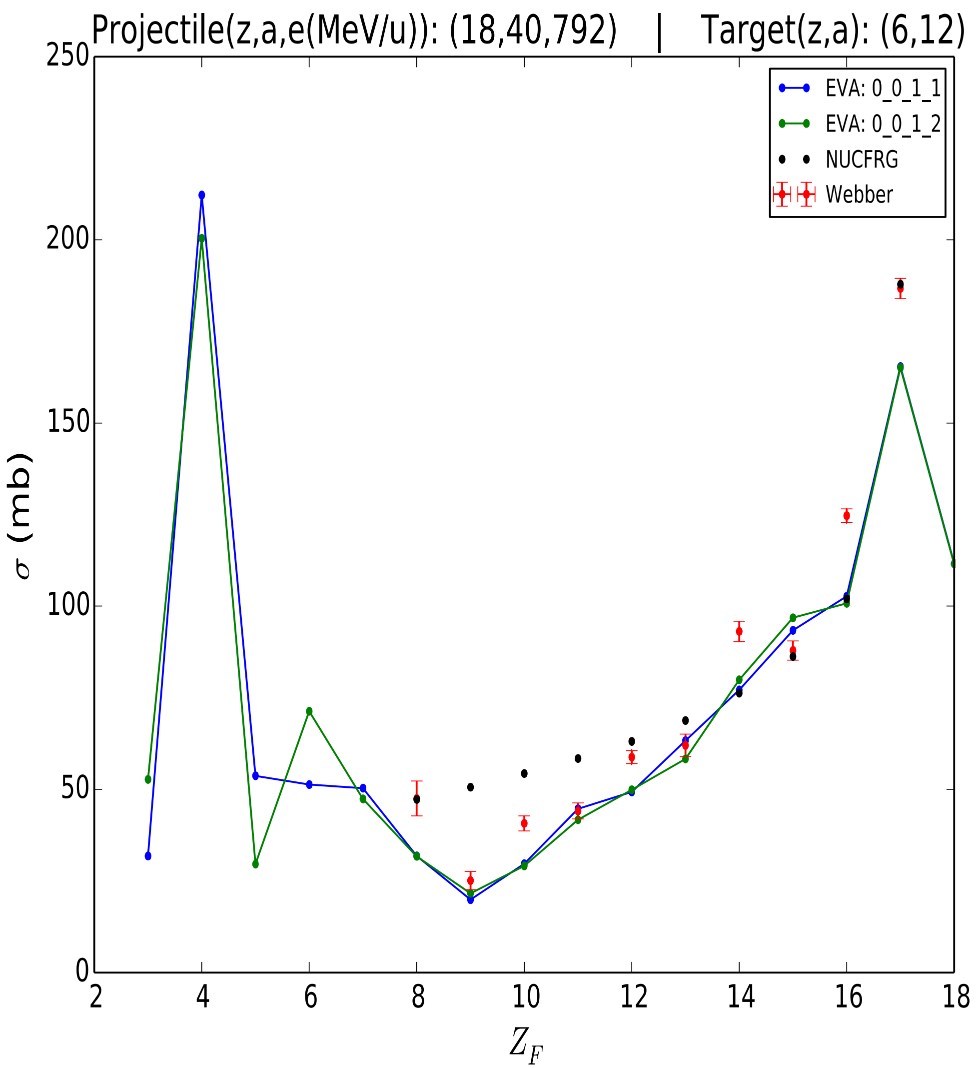
Ablation Stage Formalism

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



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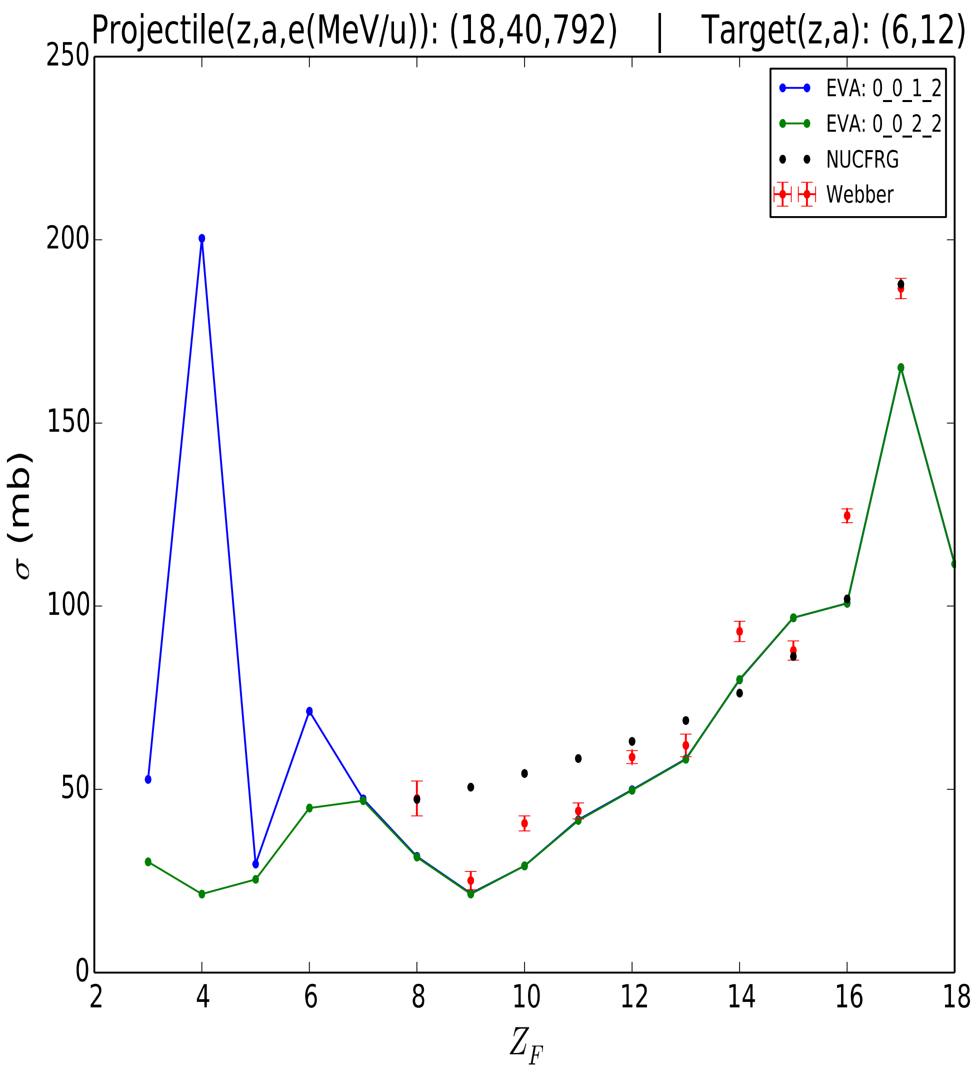
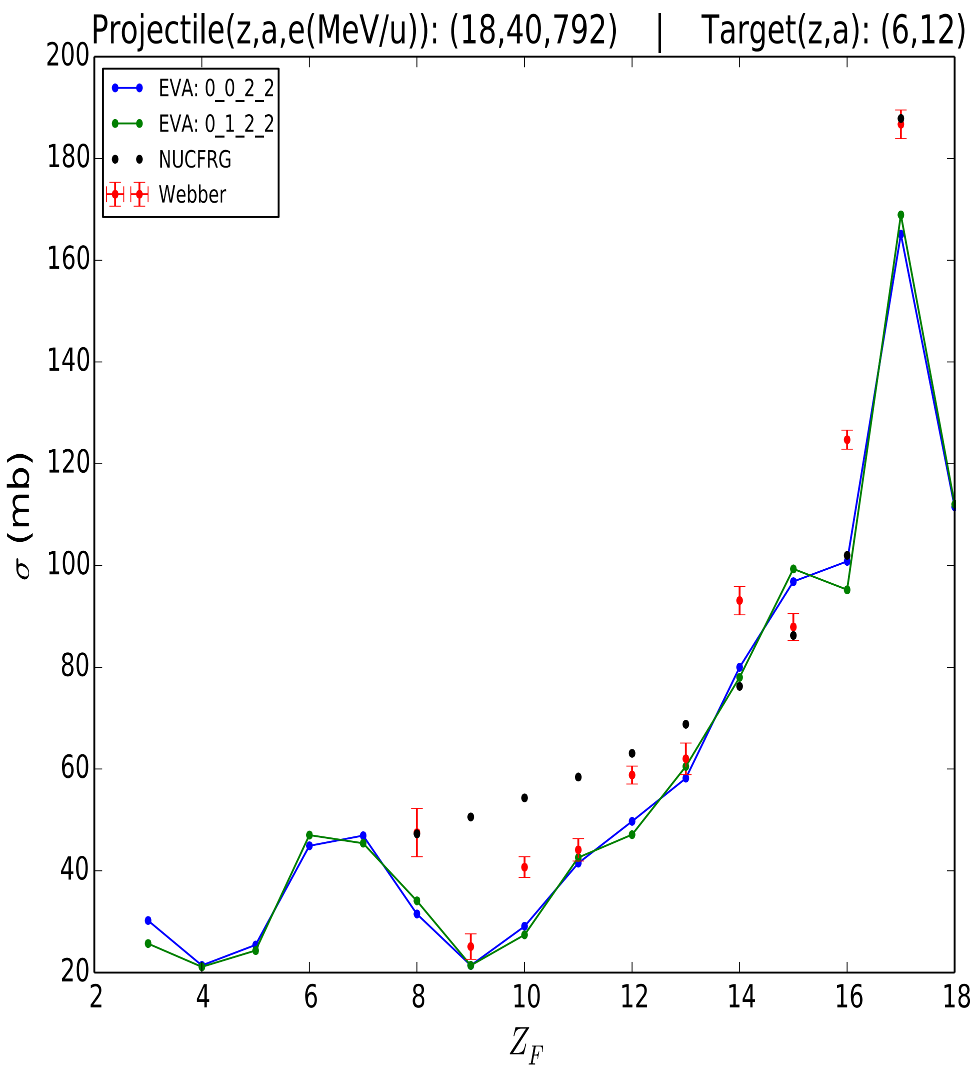
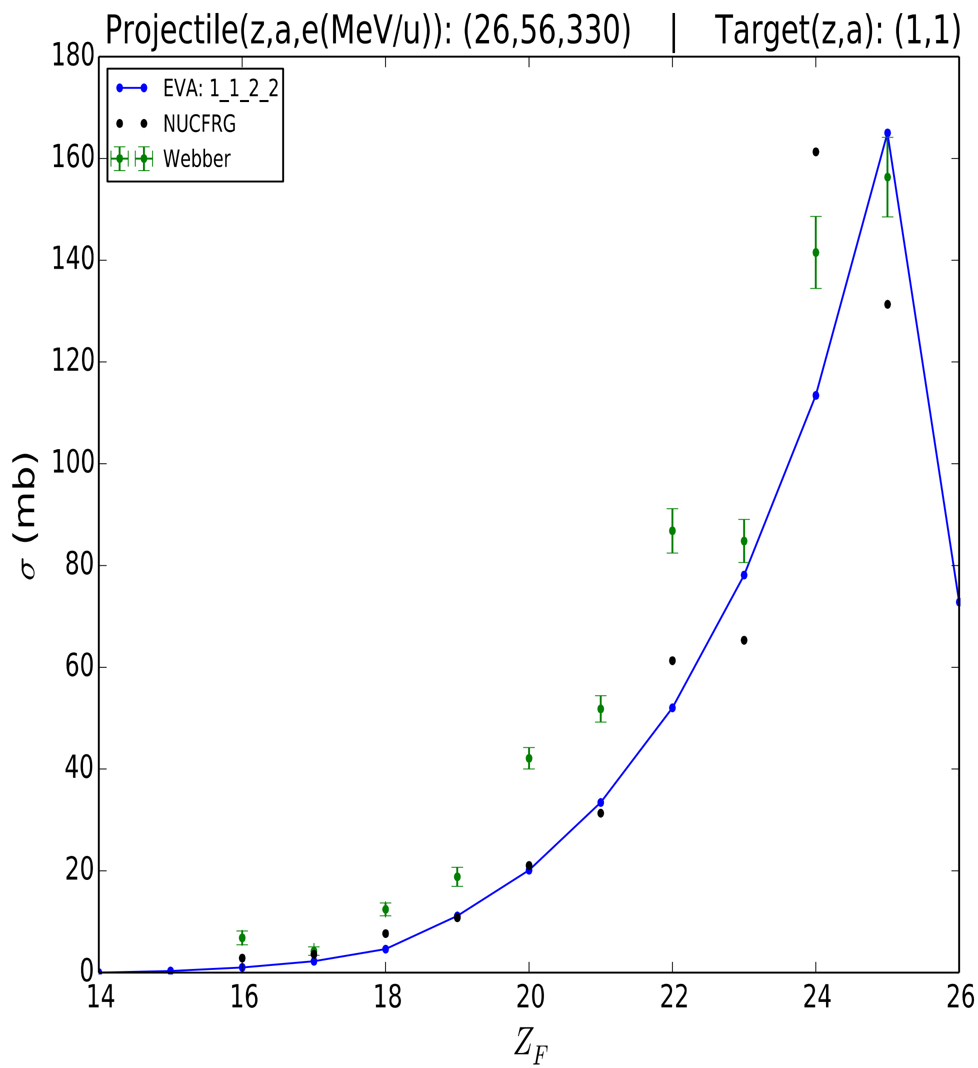


EVA Legacy & Improvements: Pairing Energy

- 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



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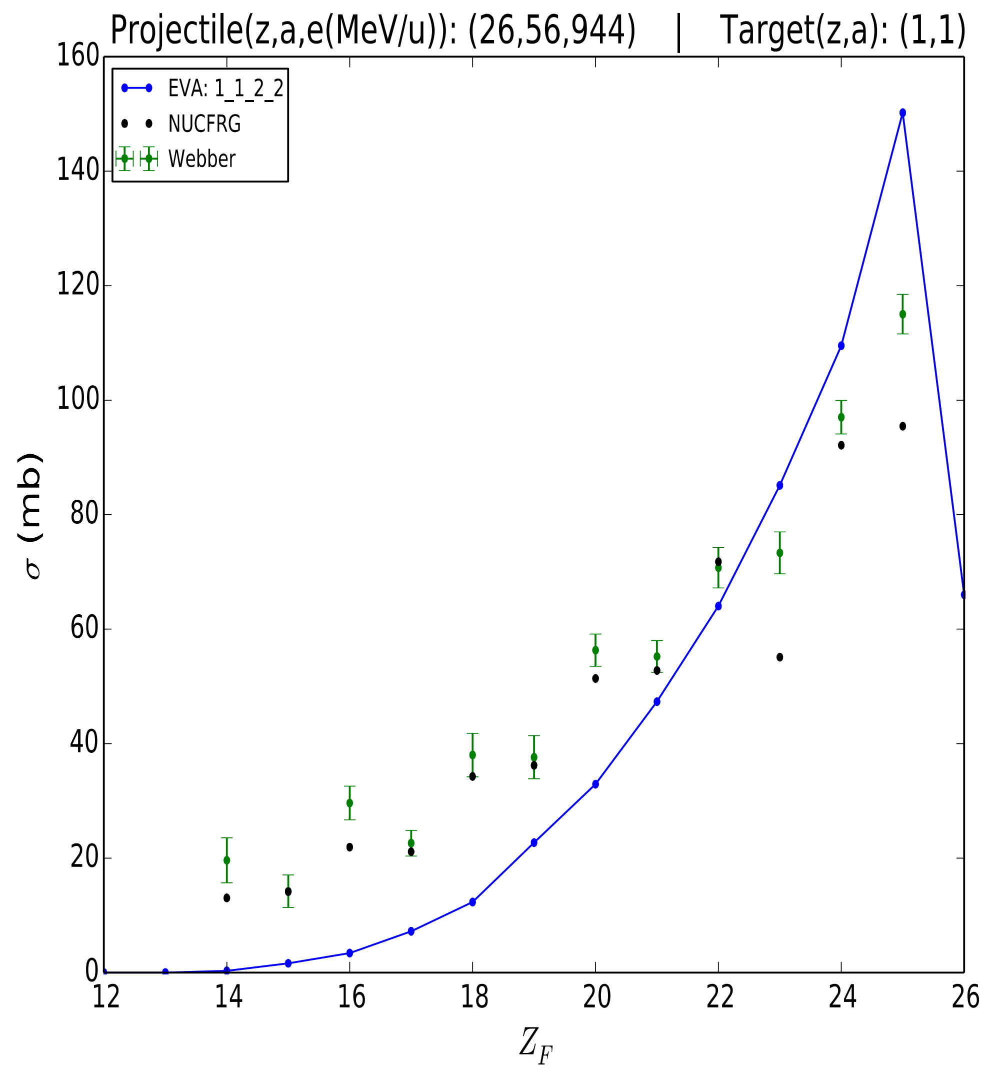

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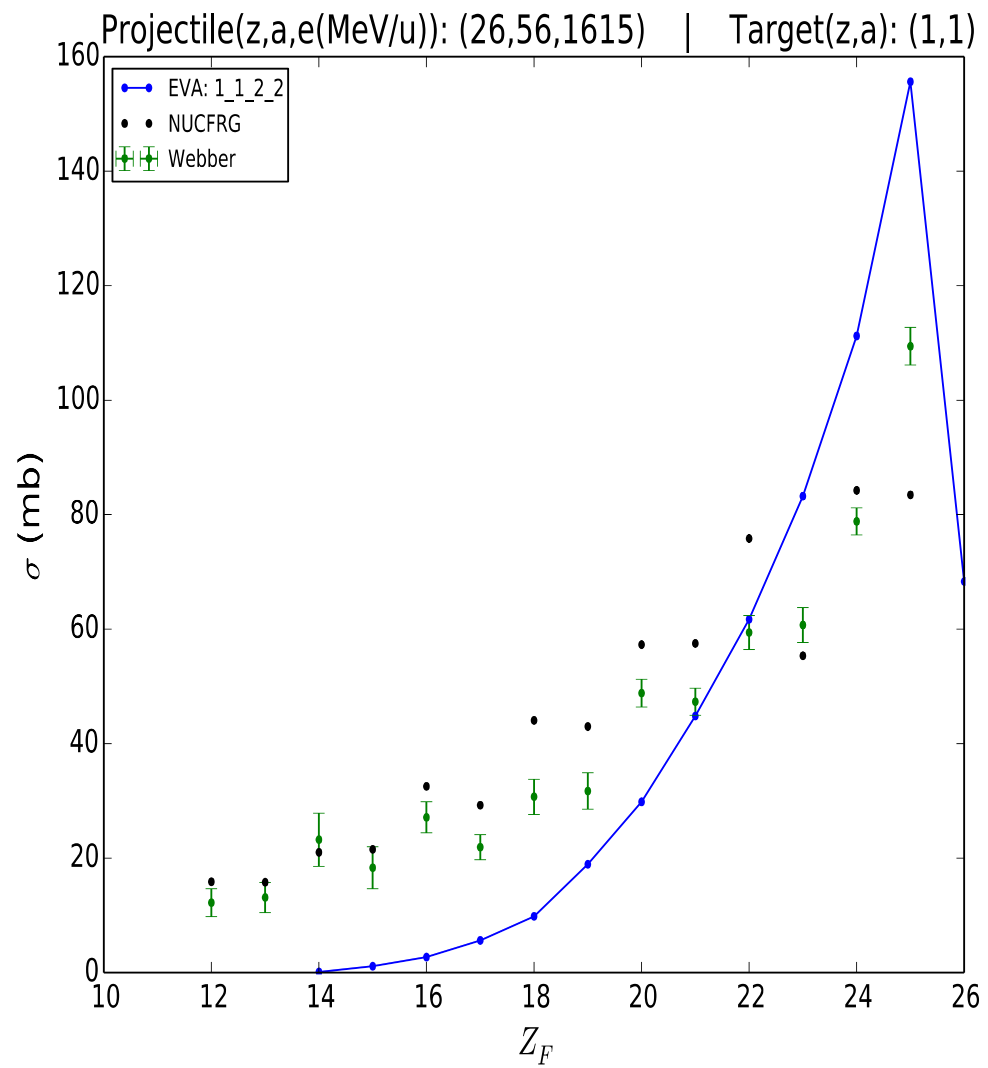

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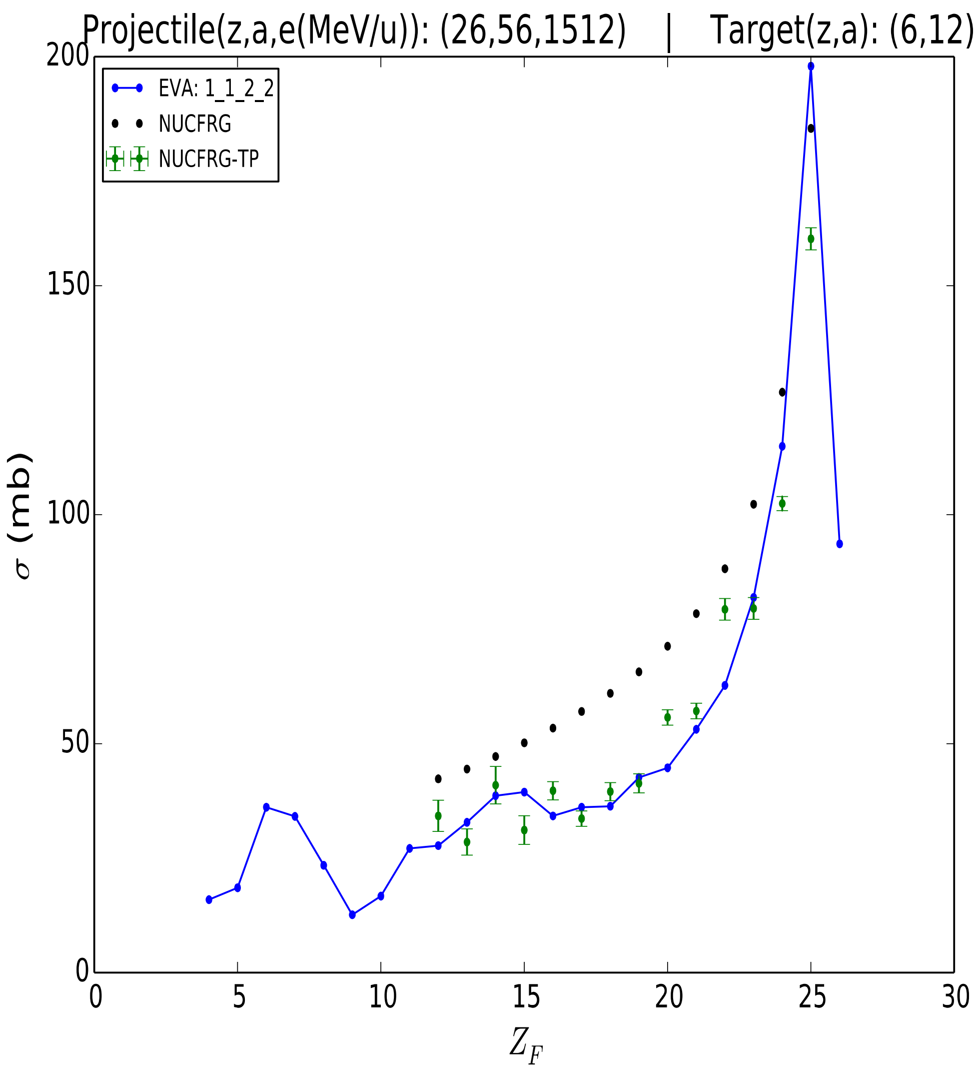

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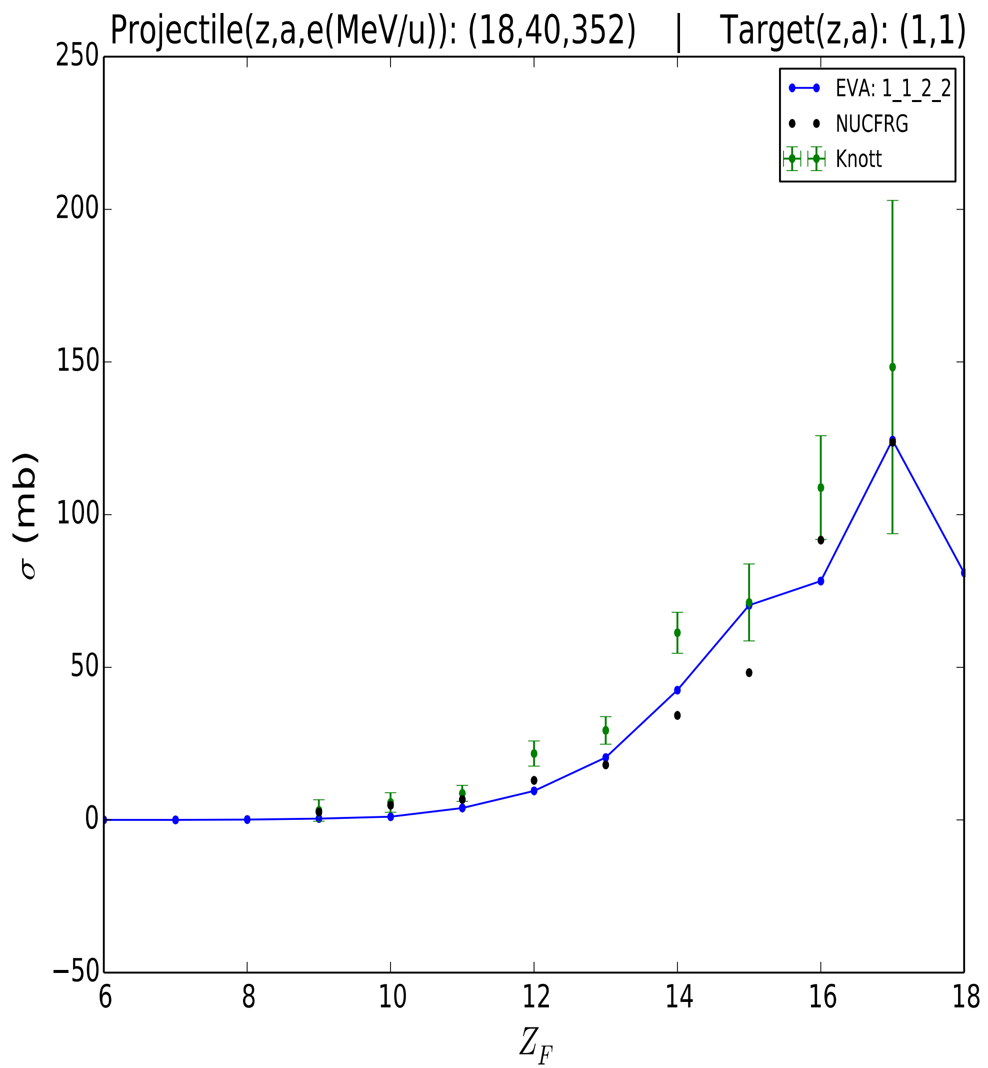

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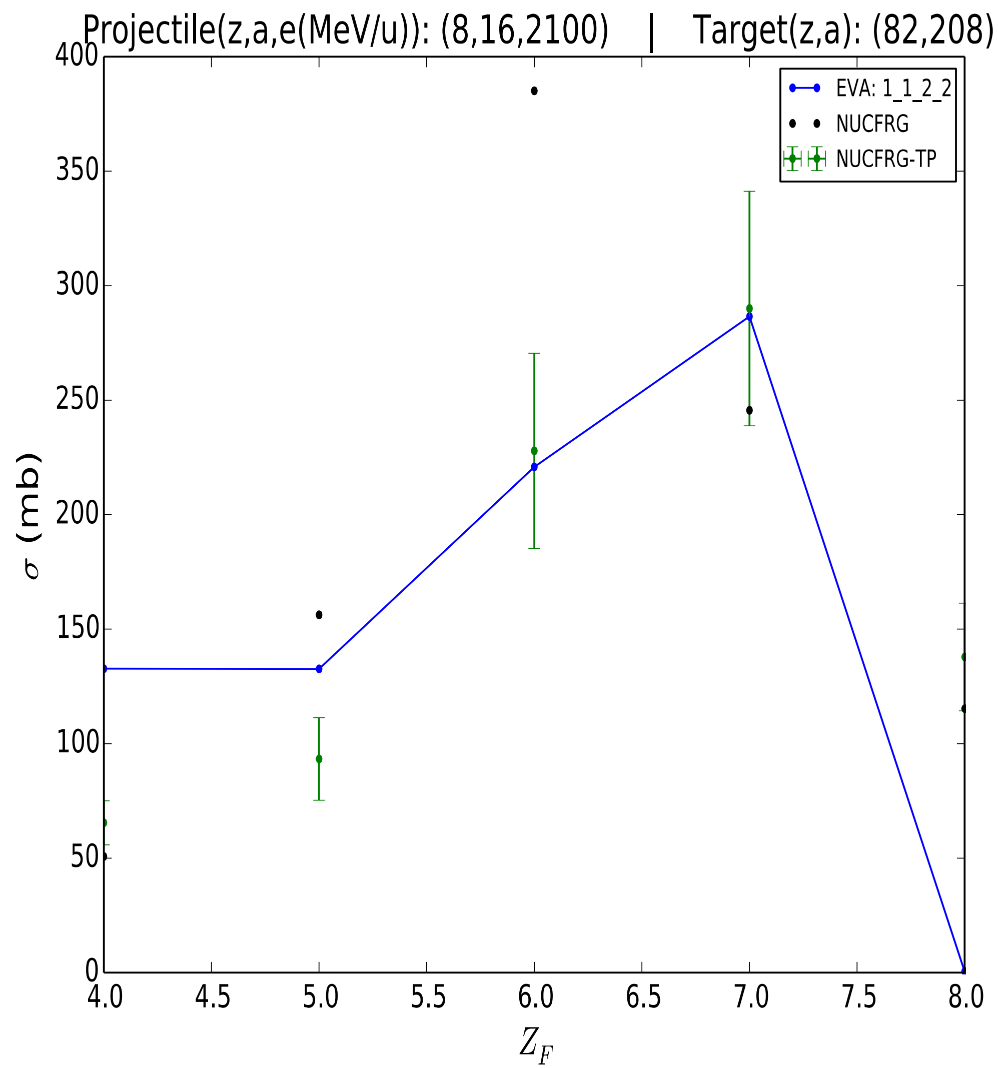

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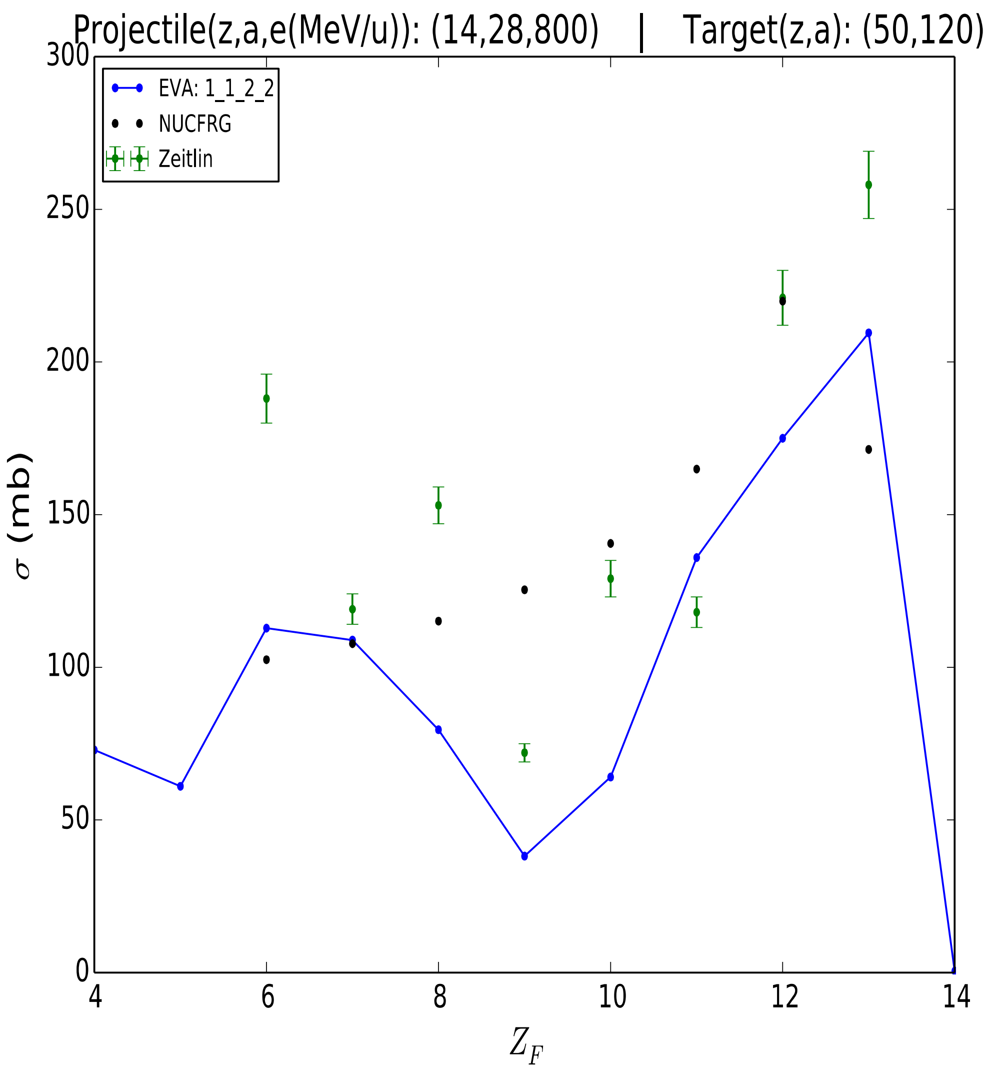

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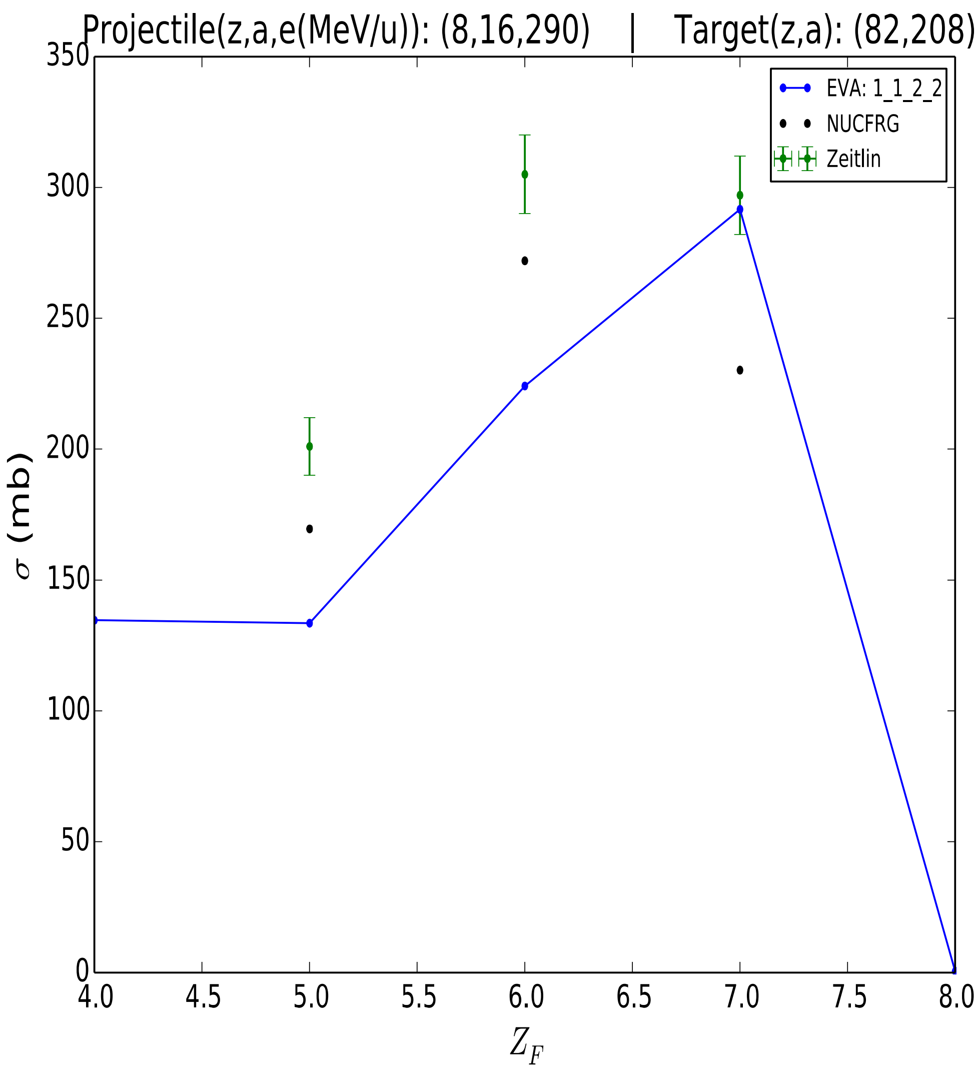
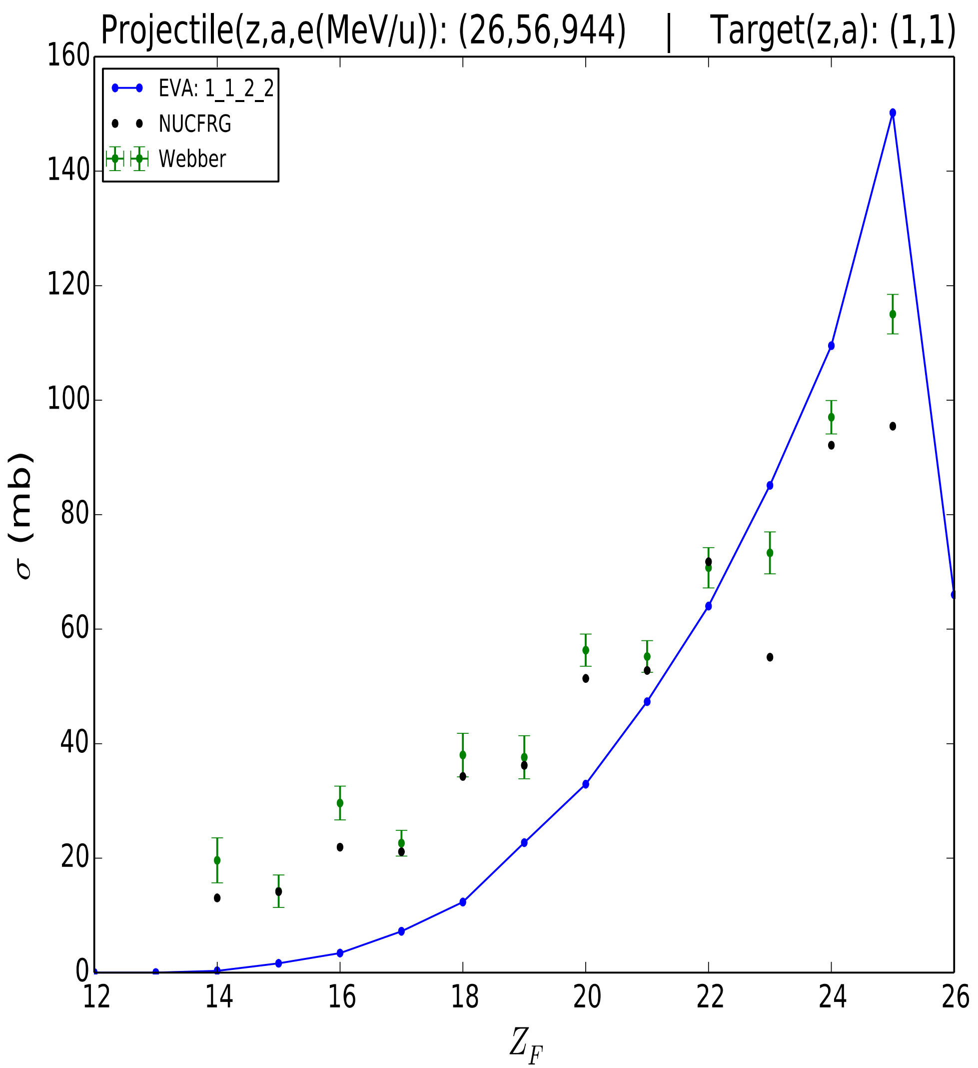


Sensitivity Study: Excitation Energy

- 1.00 x EXS
- 1.10 x EXS
- 2.00 x EXS



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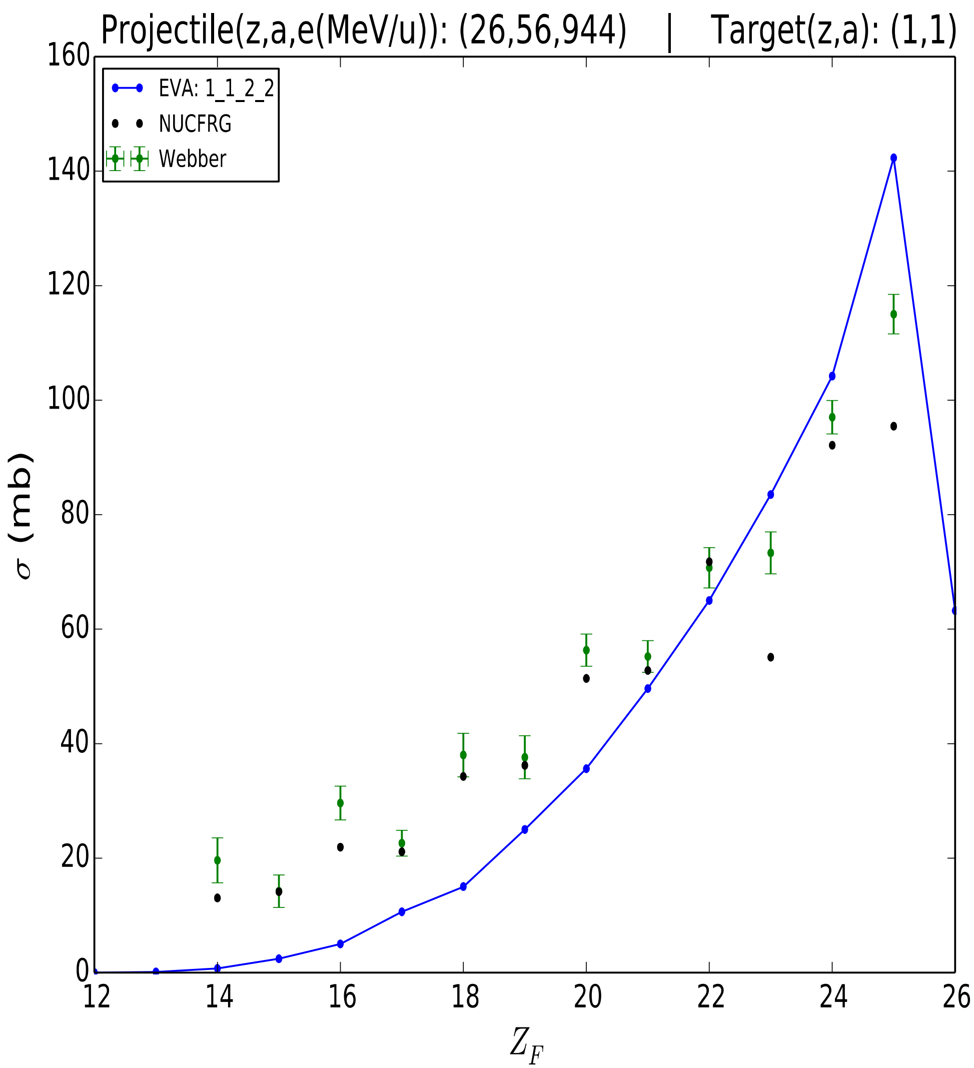

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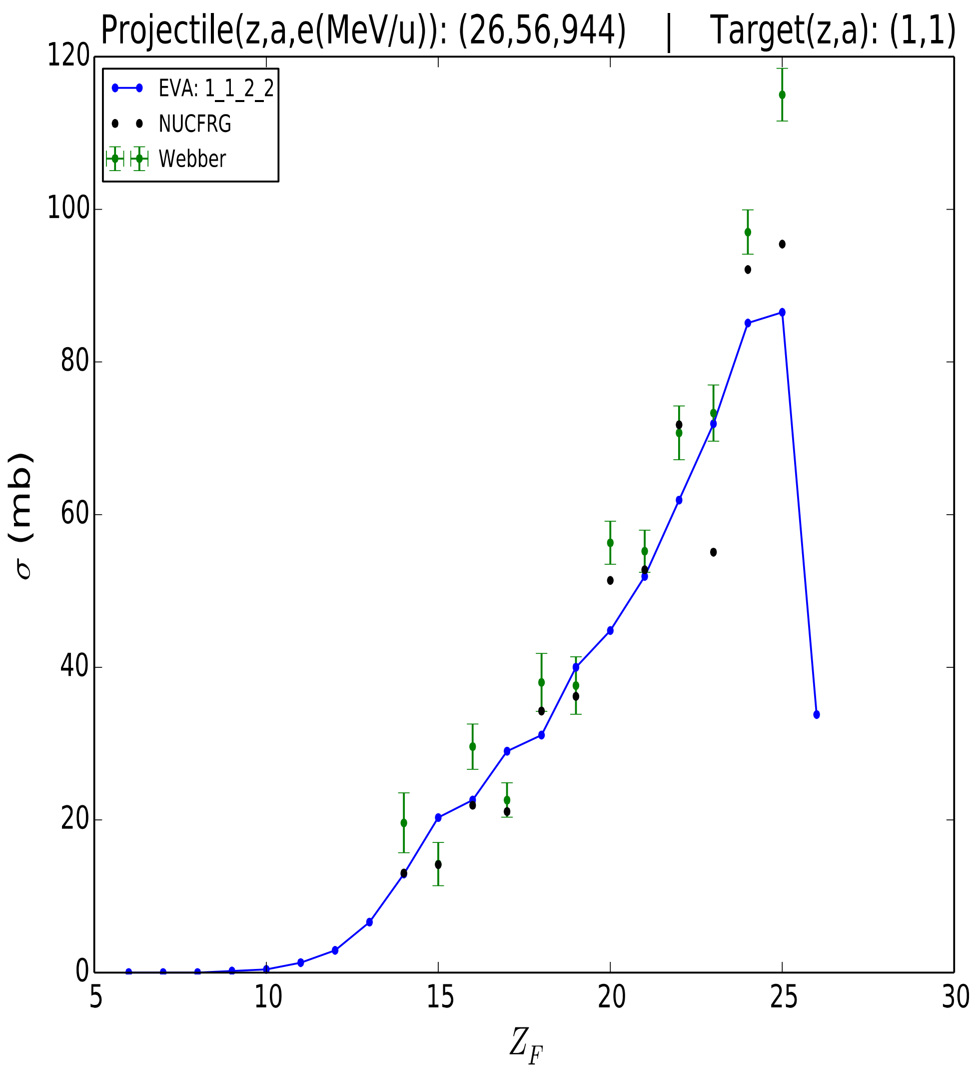

Concluding Remarks

- 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

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

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

$$\rho_j = 1.2 \text{ fm} \quad R_0 = 1.5 \text{ fm}$$

- Capture Cross Section

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

$$\beta_n = \frac{2.12 A_p^{-\frac{2}{3}} - .05}{\alpha_n} \text{ MeV} \qquad \beta_j = -k_j V_j$$

$$\alpha_n = .76 + 2.2 A_p^{-\frac{1}{3}} \qquad \alpha_j = 1 + c_j$$

Ablation: Theory & Methodology

Choosing the Kinetic Energy

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

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

$$\boxed{P_j^{\text{code}}(x) = \frac{x + \beta_n}{x_{\text{max}}} e^{-2\left(a_j x_{\text{max}} - \sqrt{a_j(\tilde{R}_j - (x+\beta_n))}\right)}}$$

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