Nuclear Fragmentation Processes Relevant for Human Space Radiation Protection

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Space radiation from cosmic ray particles is one of the main challenges for human space explorations such as a moon base or a trip to Mars. Models have been developed in order to predict the radiation exposure to astronauts and to evaluate the effectiveness of different shielding materials, and a key ingredient in these models is the physics of nuclear fragmentations. We have developed a semi-analytical method to determine which partial cross sections of nuclear fragmentations most affect the radiation dose behind shielding materials due to exposure to galactic cosmic rays. The cross sections thus determined will require more theoretical and/or experimental studies in order for us to better predict, reduce and mitigate the radiation exposure in human space explorations.
Nuclear Fragmentation Processes Relevant for Human Space Radiation Protection

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Outline

- Why do we need to address this problem?
  - Semi-analytical results
  - Constraint from baryon number conservation
  - Conclusions

For details, see ZWL, PRC75, 034609 (2007)
Space Radiation Risks in Human Space Explorations

Uncertainties in Radiation Risk Projections

Maximum Acceptable Risk (3%)

10%

1%

0.1%

0.01%

Individual’s Excess Fatality Risk

"95% Confidence Interval"

"Point Estimate"

from Cucinotta/JSC

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Heavy Ions:
small in abundance, but important for radiation effects

Galactic Cosmic Rays
(at a solar minimum)

Fluence, dose, dose-equivalent of different elements

A solar minimum GCR

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Questions to answer

Which fragmentation processes are more important? projectile(beam), fragment, energy, target, ...

Townsend et al., NASA-TM 4386 (1992)

How to best use NSRL to study space radiation physics?

NASA Space Radiation Laboratory (NSRL) at BNL
Radiation transport in one dimension

Under the straight-ahead approximation:

\[
\frac{\partial J_k(E, x)}{\partial x} = -\frac{\partial J_k(E, x)}{\Lambda_k(E)} + \sum_j \frac{\partial J_j(E, x)}{\Lambda_{kj}(E)} + \frac{\partial [w_k(E)J_k(E, x)]}{\partial E}
\]

- Flux of particle species \( k \)
- Ionization energy loss
- m.f.p. \( \Lambda_k = 1/(n\sigma_k) \)
- Total inelastic Xsection of nuclear fragmentation
- Gain of \( k \) from \( j \), \( \Lambda_{kj} = 1/(n\sigma_{kj}) \)
- Partial fragmentation Xsection \((j \rightarrow k)\)

Results in the thin-shielding limit (1)

ZWL, PRC75, 034609 (2007)

\[ J_k(E, x \to 0) \approx J_k(E, 0) \left[ 1 + w_k'(E)x + \frac{J'_k(E, 0)}{J_k(E, 0)} w_k(E)x - x \frac{1}{\Lambda_k(E)} \right] + \sum_j \frac{J_j(E, 0)}{\Lambda_{kj}(E)}x \]

Affected by cross section uncertainties, but not by energy loss

Radiation hazard is often represented by dose equivalent:

\[ H(x) = \frac{1}{\rho_T} \sum_k \int J_k(E, x) L_k(E) Q(L_k(E)) dE \]

LET in water

ICRP60(91) quality factor

When \( \sigma_{kj} \) changes:

\[ \delta H(x) = \frac{n x}{\rho_T} \sum_j \int J_j \left[ -L_j Q(L_j) \delta \sigma_j + \sum_k L_k Q(L_k) \delta \sigma_{kj} \right] dE \]

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Unitarity constraint from baryon number conservation

Assuming no anti-baryon productions (exact below $\sim 6\text{GeV/u}$), we have

$$A_j \sigma_j(E) = \sum_k A_k \sigma_{kj}(E)$$

$\Rightarrow A_j = \sum_k A_k N_k$  
This means: getting the same number of nucleons before & after a projectile fragmentation:

Not respecting unitarity means the violation of baryon number conservation
Goal of our study is:

*evaluate effects on radiation hazard from uncertainty of each single partial cross section $\sigma_{kj}$*

$\rightarrow$ *do not change all the other partial cross sections whenever possible*

The unitarity constraint from **baryon number conservation**

$$A_j \delta \sigma_j (E) = \sum_k A_k \delta \sigma_{kj} (E)$$

$\rightarrow$ The only way is to adjust $\sigma_j$ (total) according to unitarity:

when one $\sigma_{kj}$ (partial) is changed to study its effect, $\sigma_j$ (total) needs to be changed accordingly.

$$\frac{\partial J_k (E, x)}{\partial x} = -\frac{\partial J_k (E, x)}{\Lambda_k (E)} + \sum_j \frac{\partial J_j (E, x)}{\Lambda_{kj} (E)} + \frac{\partial \left[ w_k (E) J_k (E, x) \right]}{\partial E}$$
Results in the thin-shielding limit (2): include unitarity

When $\sigma_{kj}$ changes:

$$\delta H(x) = \rho x \sum_{j,k} U_{jk} \delta \sigma_{kj},$$

$$U_{jk} = \frac{n}{\rho_T \rho} \int_{L_1} J_j \left[ -Z^2 Q(Z^2 L_1) \frac{A_k}{A_j} + Z_k^2 Q(Z_k^2 L_1) \right] dE$$

- $U_{jk} \to 0$ when $Z_k \to Z_j$ or $Z_k \to 0$

- In the limit of same $Q_k$ and same $A_k/Z_k$ (for all $k$):

$$-U_{jk} \sim Z_j^2 \frac{A_k}{A_j} - Z_k^2 \approx Z_k (Z_j - Z_k)$$

$\Rightarrow U_{jk}$ peaks at $Z_k \approx Z_j / 2$

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sensitivity matrix elements

\[-U_{jk} \sim Z_k (Z_j - Z_k)\]

for 1977 solar minimum GCR

Fragment peaks at mid-Z \( Z_k \approx Z_j / 2 \)

\(-U_{jk} \rightarrow 0 \) when \( Z_k \rightarrow Z_j \) or \( Z_k \rightarrow 0 \)

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sensitivity matrix elements
without the unitarity constraint $U_{jk} \sim Z_k^2$

Fragment peaks at high-Z $Z_k \approx Z_j$
Sensitivity matrix for relative change in $\sigma_{kj}$ (e.g. 10%)

$$\delta H(x) = \rho x \sum_{j,k} S_{jk} \frac{\delta \sigma_{kj}}{\sigma_{kj}}, \quad S_{jk} = U_{jk} \sigma_{kj}$$

Light fragments are the most important

Sensitivity matrix elements $S_{jk}$ for water target and 1977 solar min GCF

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Light fragments (p & alpha) are the most important; many projectiles are important (Fe, Si, Mg, O)
Thick shielding

sensitivity matrix elements

\[ S_{jk} \]

At 20 cm in water

Medium-sized projectiles (O, Mg, Si) may become more important than Fe

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Conclusions

- Semi-analytical results show:
  Light fragments (p & alpha) are the most important;
  Many projectiles are important (Fe, Si, Mg, O)

- Focused study on these projectiles and fragments
  will most efficiently reduce uncertainty
  in evaluation of radiation hazard in human space explorations
Partial cross sections of fragmentation

Ca projectile (1.2GeV/u) in Al target:
Effect of unitarity on sensitivity matrix $S_{jk}$

\[ -S_{jk} \text{[cSv/yr][g/cm}^2] \]

\[ S_{jk}' \text{[cSv/yr][g/cm}^2] \]

\begin{align*}
\text{with unitarity} & \\
A_j \delta \sigma_j(E) &= \sum_k A_k \delta \sigma_{kj}(E)
\end{align*}

Unitarity constraint is critical for fragment distributions

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Effect of unitarity on fragment distributions

![Diagram showing the effect of unitarity on fragment distributions. The left panel shows distributions with unitarity, while the right panel shows distributions without unitarity. The y-axis represents the number of fragments per zone (Zk), and the x-axis represents the fragment zone (Zk). The graphs compare low Zk and high Zk distributions, illustrating the impact of unitarity on the distribution profile.](image-url)
Different implementation of unitarity

- The only way to have a **well-defined** sensitivity study:
  adjust $\sigma_j$ (total) according to unitarity after changing a $\sigma_{kj}$ (partial).

- Correlations among $\sigma_{kj}$ uncertainties in data:
  make the sensitivity study ill-defined,
  may require different implementation of unitarity

  **Example 1:** if $\sigma_j$ (total) is much more accurately determined than $\sigma_{kj}$ (partial)
  -> Keep $\sigma_j$ the same and make correlated changes on at least 2 $\sigma_{kj}$
  -> Results will be different depending on choice of other $\sigma_{kj}$

  **Example 2:** experimental systematic errors correlate several $\sigma_{kj}$

- Need to investigate experimental data to determine how to implement unitarity