

Cross sections for space radiation protection

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1 Introduction to Space Radiation

An important safety priority for human spaceflight is the protection of astronauts from the harmful effects of the radiation environment in space [1–4]. The three main sources of radiation exposure are geomagnetically trapped particles (mostly protons and electrons) [5], solar energetic particles (mostly protons and light ions) [6], and galactic cosmic rays (GCR). The GCR contribution is of primary importance for long-duration missions to the Moon, Mars, and other deep-space destinations where little or no natural atmospheric and magnetospheric shielding is available [3, 7]. The relevant part of the cosmic-ray spectrum includes all nuclei up to nickel with energies up to tens of GeV/n. Nuclei of higher mass or energy are not relevant to radiation protection because of their much lower flux. This radiation field interacts with a spacecraft’s hull and structures and is significantly modified via electronic energy loss, fragmentation, and nuclear interactions [8] by the time it reaches an astronaut inside the vessel [9, 10]. It is then modified even further throughout the astronaut’s body [11]. The most important particles that contribute to the radiation environment inside a spacecraft or habitat are neutrons [12–14], protons [15], light ions (i.e., isotopes of hydrogen and helium), and pions [16]. All these particles are light in mass and are therefore scattered at large angles. Thus, fully three-dimensional transport codes, which use double-differential (in solid angle and energy) cross sections as input, are required to assess how spacecraft shielding alters the primary cosmic-ray radiation field.

2 Transport Code Disagreements

To date, most spacecraft shielding has been relatively thin, with typical aerial thicknesses of about 20 g/cm² (compare to 1000 g/cm² and 20 g/cm² for Earth’s and Mars’ atmospheres, respectively). The shielding of the International Space Station (ISS), for example, shows considerable variation, from less than 10 g/cm² to about 100 g/cm² or more. Figure 1 shows the results of a variety of transport-code calculations that assess the dose equivalent produced by the full GCR spectrum in a detector between two slab shields of varying thickness [17]. As the shielding increases, the dose equivalent drops steadily and reaches a minimum around 20 g/cm², beyond which it starts to rise again due to the increased production of secondary particles. The existence of this minimum shows that there is an optimal shield thickness for radiation protection if only GCR are taken into account [17]. To efficiently protect against solar energetic particles [18], Martian and lunar habitats for crewed long-duration missions will be well beyond

this optimal thickness, reaching several hundreds of g/cm^2 . Good radiation protection criteria will thus need to rely heavily on accurate and reliable estimates of the radiation environment inside these thick shields. Unfortunately, the transport-code calculations presented in Figure 1 show disagreements on the order of 30% or more at large shielding depths.

The key question is: What is the source of this large variation and what can be done about it? The main reason for the disagreement between the codes are the different nuclear-reaction models they use, which is nicely illustrated by Figure 1. For example, two different nuclear models, QMD and INCLXX, are used as input to the otherwise identically configured Geant4 Monte Carlo framework [19, 20], showing variation of about 10% at large shielding depth. Another example is the deterministic transport code HZETRN [21–24] that was evaluated with three different nuclear models, producing even larger variations of about 40%. The other Monte Carlo codes (FLUKA [25, 26], PHITS [27, 28], and MCNP6 [29]) did not allow to change their underlying nuclear models, though it can be argued that they are among the primary differences between the otherwise similar codes [30]. Clearly, the key to resolving the observed disagreements hence lies in significantly improving the nuclear-reaction models. What, then, is the obstacle to doing so? It is not the shortage of models or the lack of nuclear theorists working on model development. Rather, it is the lack of sufficient experimental cross-section data that would allow to validate the available models.

3 Nuclear Data: Availability and Gaps

Norbury et al. [31] performed an exhaustive survey of the availability of nuclear-reaction cross-section data for charged-nuclei production relevant to space radiation protection. An example highlighting the availability of double-differential cross sections for nucleus-nucleus reactions producing alpha (^4He) particles is shown in Figure 2. The presence of the symbol “D” on the plots indicates that experimental data is available for a given projectile–target combination (the quality of the data is not ascertained). Figure 2a shows that below the pion-production threshold (280 MeV/n), there is an abundance of data available for a variety of targets and for projectile charges $Z_P \leq 10$. Above $Z_P = 10$, there is very little data. The same is true to a lesser extent for projectile energies, T , between the pion threshold and 3 GeV/n, as shown in Figure 2b. Figure 2c shows that for $3 \text{ GeV/n} < T < 15 \text{ GeV/n}$, there are only two data sets; for $T > 15 \text{ GeV/n}$, no data is available. Figure 2 only shows the production of alpha (^4He) particles, but Norbury et al. [31] compiled measurement data for a broad range of nuclear fragments and types¹ of cross sections (total, charge-changing, single-differential, etc.).

The most important reference for neutron production data is that by Nakamura and Heilbronn [32]. They collected all of the existing world data for both cross sections and thick-target

¹Yield distributions were not included because they cannot be used without prior conversion into cross sections.

yields. Most of the data came from experiments at the RIKEN², HIMAC³, and Bevalac⁴ accelerators. Subsequently, Satoh et al. [33] and Itashiki et al. [34] reported more data, some of which overlaps with that listed in reference [32], enabling comparisons between experiments. When one analyzes all these data, some significant disagreements are found. Bevalac data (337 MeV/n) [32] show inconsistencies with HIMAC data, though the recent measurements by Satoh and Itashiki are broadly consistent with the latter. The low-energy (95 MeV/n and 135 MeV/n) RIKEN data [32] also show some inconsistencies. Overall, the complete neutron data set needs a re-evaluation and extensive new experimental data to resolve disagreements between the different available measurements.

4 Recommendations

The primary projectiles of interest for future measurements of light-ion production relevant to space radiation protection are Fe, Si, O, and He. Energies of interest are between 100 MeV/n and 10 GeV/n, with an emphasis on data at higher energies, where there are significant data gaps. Other projectiles and energies above 10 GeV/n are also of interest for testing models and transport codes if such data is all that is available. A variety of targets are of interest, including the major constituent elements of the most commonly used aerospace materials and the human body (e.g., H, C, Al, Fe). To be useful as input to nuclear-reaction models (and hence transport codes), measurements must determine double-differential and total-reaction cross sections and identify fragments and secondary particles over as broad an energy range as possible. For secondary particles, pions are of particular interest, for which production cross sections should be measured with high precision.

There are also a variety of other measurement needs, the most important being double-differential cross sections for neutron production, especially above 1000 MeV/n, where there is essentially no data, and for energies as low as 1 MeV, where the biological damage from neutrons is the largest [35]. Many measurements of yield distributions are already available in the literature (see, e.g., [36]), for which it would be very helpful if a methodology was developed to reliably convert them into cross sections. Finally, extensive comparisons of the most important nuclear models used in transport codes are needed, including validations against currently available and future measurements.

5 Summary

Uncertainties in predicting radiation-related health effects due to exposure to the space radiation environment are one of the major challenges for human spaceflight beyond Earth orbit

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[37–39]. In shielded environments, light ions (i.e., isotopes of hydrogen and helium) and neutrons make the largest contributions to the dose equivalent astronauts receive. The largest uncertainties in predicting radiation doses and the associated health risks stem from a limited understanding of radiation biology and from disagreements in transport codes [40–42]. The latter are primarily caused by inadequate knowledge about the light-ion production cross sections [17, 43], which also constitute the largest gap in currently available nuclear data [31]. It is therefore imperative that these cross sections be measured to place space radiation protection on a solid foundation.

Measurement Priorities for Space Radiation Protection

1. Light-Ion Production: ${}^1,2,3\text{H}$, ${}^3,4\text{He}$

Projectiles: He, O, Si, Fe

Projectile kinetic energies: 100 MeV/n to tens of GeV/n

Targets: H, C, Al, Fe

Cross section types: Isotopic double-differential and total-reaction

2. Neutron Production

Projectile kinetic energies: < 1000 MeV/n

Neutron kinetic energies: all energies, including near 1 MeV

Projectiles: He, O, Si, Fe

Targets: H, C, Al, Fe

Cross sections types: Double-differential and total-reaction

→ Resolve disagreements between different available measurements

Projectile kinetic energies: > 1000 MeV/n

Neutron kinetic energies: all energies, including near 1 MeV

Projectiles: He, O, Si, Fe

Targets: H, C, Al, Fe

Cross section types: Double-differential and total-reaction

3. Pion Production

Projectiles: He, O, Si, Fe

Projectile kinetic energies: 100 MeV/n to tens of GeV/n

Cross section types: $\pi^\pm$ double-differential and total-reaction

4. Other Needs

- Existing yield data needs to be reliably converted to cross sections.
- Many existing data sets need to be reproduced and confirmed for accuracy for production of light ions, neutrons, and pions.
- Collaborations are needed to perform comprehensive comparisons of the most important nuclear models used in transport codes.
- Models should be compared to each other and also to experimental data.

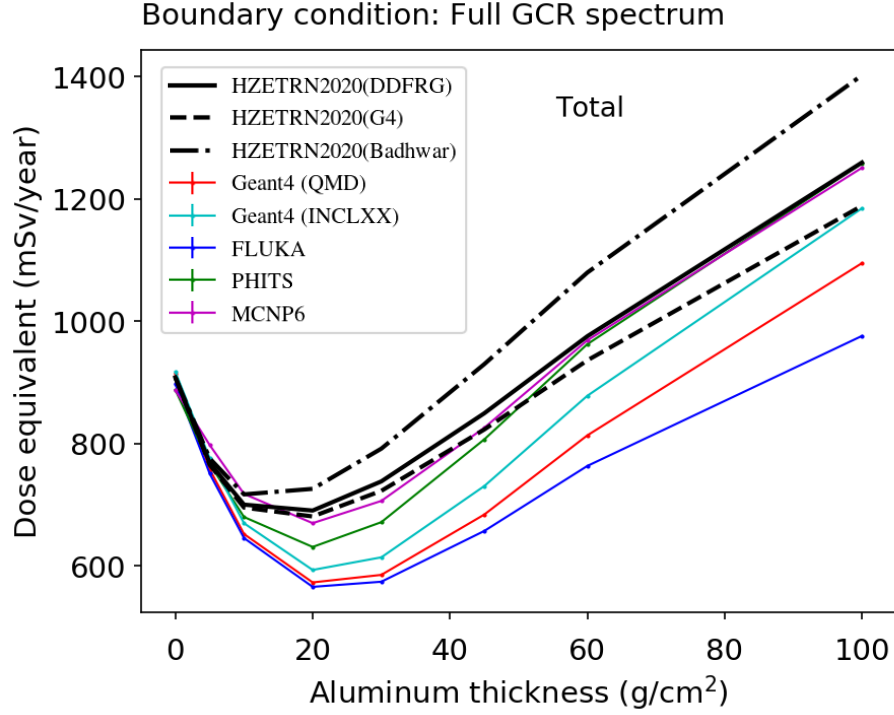
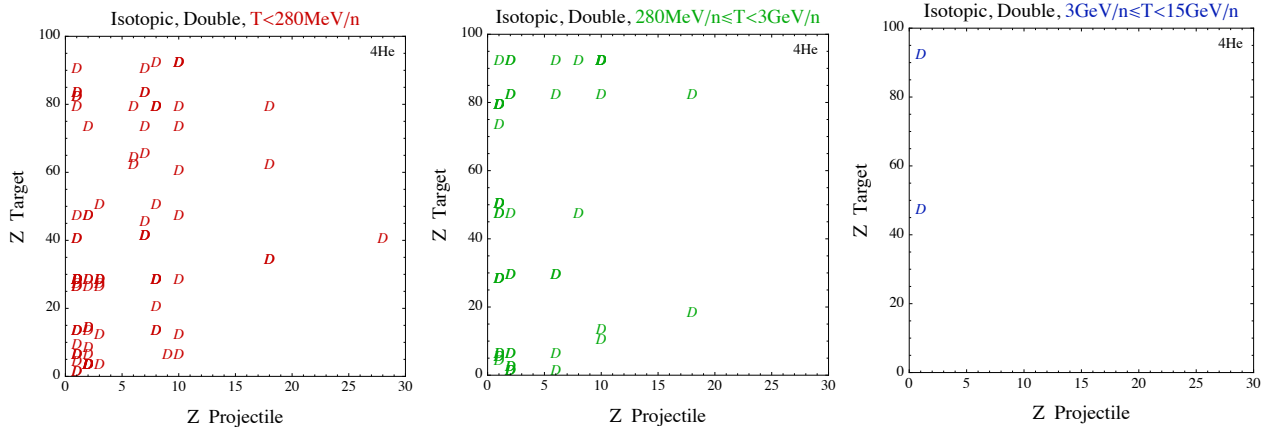


Figure 1: Simulated dose equivalent (total all particles) as a function of shielding depth for a detector exposed to the full GCR spectrum and located between two slab shields, *each* of the thickness indicated on the horizontal axis. The results of the Geant4 Monte Carlo code [19, 20] with the QMD and INCLXX nuclear models are shown in red and cyan, respectively. Those of the HZETRN [21–24] transport code with three different nuclear models (DDFRG [44, 45], Badhwar [46], and G4, where G4 refers to the INCLXX model from Geant4) are shown as solid and dashed black lines. The other evaluated Monte Carlo codes are FLUKA (blue) [25, 26], PHITS (green) [27, 28], and MCNP6 (purple) [29]. Updated version of Figure 13 in reference [17], provided by Tony Slaba.



(a) $T < 280 \text{ MeV/n}$. (b) $280 \text{ MeV/n} \leq T < 3 \text{ GeV/n}$. (c) $3 \text{ GeV/n} \leq T < 15 \text{ GeV/n}$.

Figure 2: Example of nuclear-reaction double-differential cross section measurements available for the production of alpha (^4He) particles from nucleus-nucleus reactions. Each panel shows the availability of measurements (represented by the symbols "D") for different projectile kinetic energies, T . There are no measurements available for $T > 15 \text{ GeV/n}$. Figure reproduced from reference [31].

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