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How Space Radiation Risk from Galactic Cosmic Rays at the International Space Station Relates to Nuclear Cross Sections

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Space radiation risk to astronauts is a major obstacle for long term human space explorations. Space radiation transport codes have thus been developed to evaluate radiation effects at the International Space Station (ISS) and in missions to the Moon or Mars. We study how nuclear fragmentation processes in such radiation transport affect predictions on the radiation risk from galactic cosmic rays. Taking into account effects of the geomagnetic field on the cosmic ray spectra, we investigate the effects of fragmentation cross sections at different energies on the radiation risk (represented by dose-equivalent) from galactic cosmic rays behind typical spacecraft materials. These results tell us how the radiation risk at the ISS is related to nuclear cross sections at different energies, and consequently how to most efficiently reduce the physical uncertainty in our predictions on the radiation risk at the ISS.

1. Introduction

Space radiation to astronauts is a major hazard for long-duration human space explorations. Two major sources of space radiation are the galactic cosmic rays (GCR) and solar energetic particles (SEP). GCR are ever-present and more energetic, thus they are able to penetrate much thicker materials than SEP. In order to evaluate the space radiation risk and design the spacecraft and habitat for better radiation protection, space radiation transport codes, which depends on the input physics of nuclear interactions, have been developed. Both ground-based and airborne experiments have been and will be used to improve the theoretical modeling of nuclear fragmentations as a function of energy and thus improve the accuracy of these transport codes. This study focus on the propagation of space radiation particles in materials, and the deterministic code HZETRN [1] is used in this study. A detailed sensitivity analysis to energy in deep-space GCR environments can be found in Ref. [2]. At the International Space Station, however, the geomagnetic field from the Earth affects the flux of charged particles at different energies differently. Fig. 1 shows the geomagnetic transmission function at the ISS (including the shadowing effect from the Earth) as a function of magnetic rigidity, while in deep space the function is unity by definition as there are no geomagnetic or shadowing effects. Therefore we expect different sensitivities to the energy in fragmentation cross sections, and these results tell us at what energies nuclear fragmentation most affects the GCR radiation risk at the ISS.

2. Results

A cross section as a function of energy is represented by its values at the following 18 discreet energy points $E_i(i =!1-18)$ (equally separated logarithmically by a factor of $\sqrt{2}$): 0.053, 0.075, 0.106, 0.15, 0.212, 0.3, 0.424, 0.6, 0.849, 1.2, 1.697, 2.4, 3.394, 4.8, 6.788, 9.6, 13.58, and 19.2 GeV/u. For collisions at energies below E_1 (or above E_{18}), the cross section is taken to be the same as that at the energy E_1 (or at E_{18}), while an interpolated cross section is used for collisions at energies between two adjacent energies. In order to study the sensitivity to cross sections at energy E, we change the values of cross sections at $E_i(i =!2-17)$, including all partial cross sections for all projectiles, by the same percentage Δ, while cross sections at all other energy points are unchanged. The total inelastic cross sections for all projectiles at this energy E_i also need to be increased

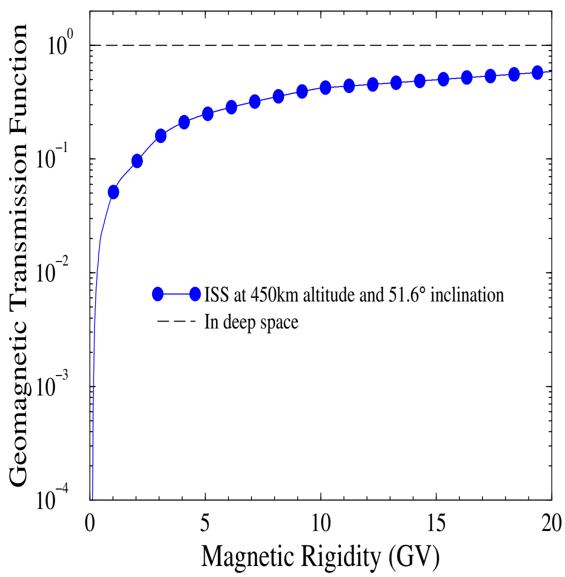

Figure 1. The geomagnetic transmission function at the ISS, with the function in deep space being unity (by definition).

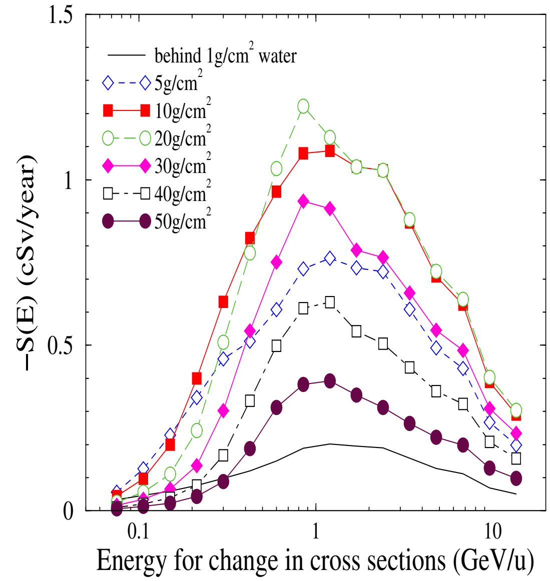

Figure 2. Sensitivity functions $S(E)$ at the ISS for the 1977 solar minimum GCR environment, showing the response of dose-equivalent behind target to changes in cross sections via Eq. (1).

by the same percentage in order to satisfy baryon number conservation, $A_j\sigma_j(E) = \sum_k A_k\sigma_{kj}(E)$, where A_j and A_k represent the atomic weight of projectile j and its fragment k, respectively, $\sigma_j(E)$ represents the total inelastic cross section of projectile j at energy E, and $\sigma_{kj}(E)$ represents the partial cross section of producing fragment k from the fragmentation of j at energy E. This relation is exact when the projectile fragmentation is separated from the target fragmentation and when baryon-antibaryon productions can be neglected [1]. Dose-equivalent is used in this study as the measure of radiation risk, and we use the latest definition of the quality factor from ICRP60 [3].

A normalized sensitivity function $S(E)$ for dose-equivalent H can be defined, at any depth in a target material, as

$$\delta H = \int S(E)\frac{\delta\sigma(E)}{\sigma(E)}d(\ln E). \quad (1)$$

This sensitivity function is then independent of the value of Δ [2] or the spacings between adjacent energy points (unless the effect is strong enough to be non-linear), and can be used to estimate the change of dose-equivalent from an energy-dependent relative change of cross sections, $\delta\sigma(E)/\sigma(E)$. If the interpolation of cross sections is linear in ln E, from calculations of δH_i at discreet energy points E_i we can extract $S(E)$ as

$$S(E_i) \simeq \frac{\delta H_i}{\Delta \ln\sqrt{2}} \quad (\text{for i}=2-17), \quad (2)$$

where the factor of $\ln\sqrt{2}$ is due to the equal energy spacing in logarithmic scale by factor of $\sqrt{2}$. The $S(E)$

[1] Note that baryon-antibaryon productions have a threshold of about 6 GeV/u and are not present in the space radiation transport code we use in this study.

curves thus obtained for water target in the 1977 solar minimum GCR environment are shown in Fig. 2. We see that they are broad Gaussian-like curves and peak at around 0.85 to 1.2 GeV/u.

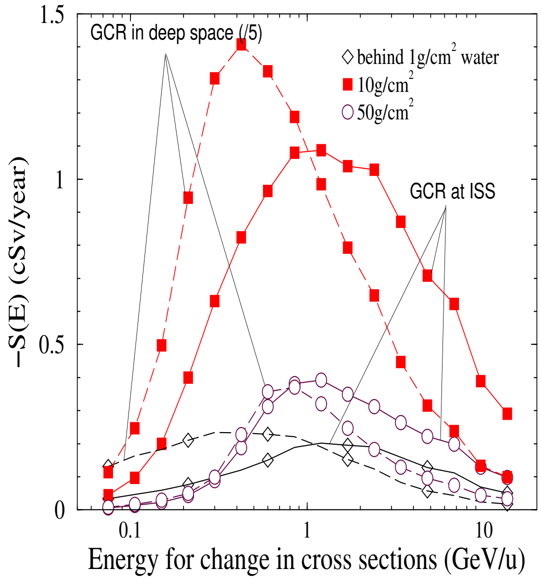

Figure 3. Sensitivity functions in the 1977 solar minimum GCR environment for water target at the ISS (solid) and in deep space (dashed, scaled down by a factor of 5).

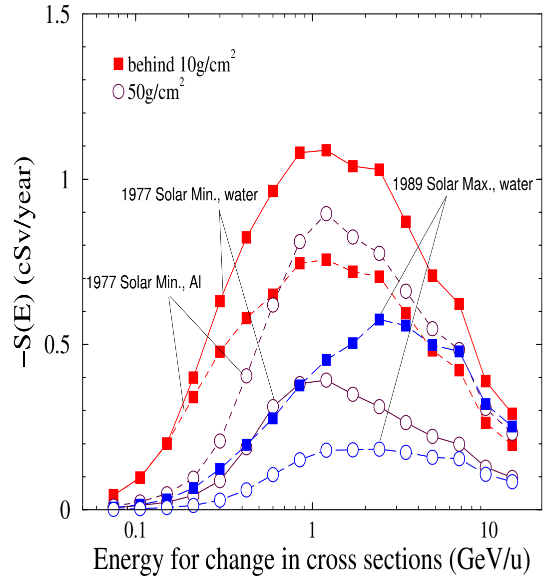

Figure 4. Sensitivity functions at the ISS behind 10 and 50 g/cm^2 water and aluminum targets in the 1977 solar minimum GCR environment and behind water target in the 1989 solar maximum GCR environment.

Fig. 3 shows that the sensitivity functions at the ISS are very different from those in deep space. At the ISS, the energies corresponding to the $S(E)$ peaks are higher (sometimes by as much as a factor of 4) than those in deep space as a result of the geomagnetic cutoff effect on low energy GCR particles. Also, the peak values of the $S(E)$ functions for the ISS at a given depth are lower roughly a factor of 5 to 7, where the shadowing effect from the Earth has also contributed. Note that the total dose-equivalent from the 1977 solar minimum GCR without shielding materials is 120 cSv/year in deep space and 15.5 cSv/year at the ISS (about a factor of 8 lower).

Fig. 4 shows the sensitivity functions for aluminum target in the 1977 solar minimum GCR environment and for water target in the 1989 solar maximum GCR environment, in addition to those for water target in the 1977 solar minimum GCR environment. We see that, for the same GCR environment, the shapes of $S(E)$ functions are similar for aluminum and water targets although the overall magnitudes at a given depth are different due to their different shielding effectivenesses. For different GCR environments, however, both the overall magnitudes and the shapes of the $S(E)$ curves are different because of changes in the abundance and average energy of the GCR particles. For the 1989 solar maximum GCR environment, the energy where cross sections have the largest effects is around 2.4 GeV/u, while for the 1977 solar minimum GCR environment it is around 0.85 to 1.2 GeV/u. Considering the finite energy resolution of this study due to the discreet energy points, we conclude that cross sections around these peak values, say from 0.6 to 3.4 GeV/u, most affect the GCR dose-equivalent behind water or aluminum targets at the ISS. Note that, for GCR in deep space, cross sections from 0.2 to 1.7 GeV/u have the largest effects [2].

In this study we have only considered the case when all cross sections in a specific energy range are changed by the same percentage, equivalent to assuming full positive correlations among different cross sections. In reality, however, fragmentation cross sections to different fragments can be unrelated or anti-related with different magnitudes, which can lead to much lower sensitivities in the dose-equivalent behind targets to cross sections. Thus this study addresses the sensitivity to the energy of fragmentation cross sections regardless of projectile and fragment combinations involved, and can be considered as a worst-case scenario or an upper limit on the sensitivity to energy. On the other hand, sensitivity studies on projectile and fragment combinations of fragmentation cross sections have been performed [4, 5], but regardless of the energy scale involved. Therefore a further study is needed to simultaneously address the sensitivity to both projectile and fragment combinations and to energy.

3. Conclusions

We have studied the sensitivity of the total dose-equivalent to fragmentation cross sections in different energy ranges at the International Space Station. Both water and aluminum targets with areal densities from 1 to 50 g/cm^2 have been evaluated. Our results show that, for solar minimum GCR environments, cross sections between 0.85 and 1.2 GeV/u usually have the largest effects on dose-equivalent behind materials. For solar maximum GCR environments, cross sections at higher energies (around 2.4 GeV/u for the 1989 GCR environment) have the largest effects; however, both the total dose-equivalent and the sensitivity to changes in cross sections are smaller for solar maximum GCR environments. As a comparison, fragmentation cross sections between 0.3 and 1.2 GeV/u usually have the largest effects in deep space GCR environments. Considering the finite energy resolution in this study, in order to reduce the uncertainty on dose-equivalent behind targets at the ISS, more emphasis can be put on fragmentation cross sections between about 0.6 and 3.4 GeV/u. Cross sections at both lower and higher energies have smaller effects on the dose-equivalent behind targets, although the sensitivity functions cover quite a broad energy range.

4. Acknowledgements

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