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Spatial resolution requirements for active radiation detectors used beyond low earth orbit

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A B S T R A C T

Measurements of the incident fluence of HZE particles, as a function of LET, are used to determine absorbed dose as well as Quality Factors for assigning risk estimates to astronauts during manned space missions. These data are often based on thin solid state detectors that measure energy deposition, *dE*, and the assumption that the trajectory of the particle, *dx*, is equivalent to the thickness of the detector. Heavy ions often fragment while penetrating shielding materials in vehicles or habitats. Projectile fragments can be clustered spatially and temporally at the location of the thin detector which are then misclassified as a single particle. Eliminating the confounding effects of coincident events is the first step in extending the reach of flight instruments to identify the charge and velocity of individual particles. Identification of individual particles, in a fragmentation spectrum, will require that detection systems have sufficient segmentation to eliminate coincident events. The objective of this study was to reduce coincident events while avoiding over-design and complexity.

Monte Carlo simulations, using Geant4, were performed for ^{4}He, ^{12}C, ^{28}Si and ^{56}Fe ions at energies of 300, 900 and 2400 MeV/n incident upon aluminum shields having areal densities of 5.4, 13.5, and 54 g/cm^2. The identity, energy and spatial distribution of all particles downstream from the shielding were analyzed using a novel approach based on proximity distributions. Results indicated that pixel dimensions on the order of 1 mm were sufficient to reduce errors caused by coincident events for active space radiation detectors.

1. Introduction

The radiation environment beyond low earth orbit is composed of two major components, solar particle events (SPE) and galactic cosmic rays (GCR). The GCR, the focus of this study, are composed of 87% protons, 12% helium ions and 1% HZE ions. GCR orginate from outside the solar system and will be omnidirectionally incident on astronauts. While the fluence of ions in space with charge $Z > 2$ is only 1% of the GCR spectrum, these high Z ions contribute significantly to the radiation dose.

HZE ions are believed to have qualitatively and quantitatively different effects on biological systems when compared to the natural radiation background found on earth (Durante, 2014). Moreover, less information is available about the effects that space radiation has on humans due to the small number of individuals exposed. An important risk to astronauts from space radiation is the induction of cancer. Noncancer effects, such as damage to the central nervous system (CNS) and late cardiovascular disease are of increasing concern and have large uncertainties in the estimated risk (Durante and Cucinotta, 2008). Data also suggest that heavy ions cause damage through non-targeted effects (Durante, 2012). The assessment of radiation risk for both acute and late effects, will be essential for ensuring the health and safety of astronauts. The National Council on Radiation Protection and Measurements (NCRP) and National Aeronautics and Space Administration (NASA) have published many documents on the appropriate methods for radiation protection in space (NCRP, 1989, 2002, 2006, 2014; Cucinotta et al., 2013).

Radiation protection in space is focused on ensuring short and long term effects of radiation are limited to acceptable levels. A quality factor, Q, is a factor that modifies the absorbed radiation dose based on biological effectiveness, and is an important concept in radiation protection. Historically Q has been defined as a function of linear energy transfer (LET). In preparation for space missions beyond low earth orbit, significant efforts have been directed towards updating quality factors to more accurately reflect the biological damage HZE particles cause (Cucinotta et al., 2013). This revised quality factor, Q_{NASA}, requires identification of the charge Z and velocity β of HZE ions in addition to LET. However, detector systems deployed into space have a limited capability to measure charge and velocity of individual particles, and do not provide sufficient information for the accurate

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determination of radiation risk to astronauts under the new NASA paradigm. Borak et al., have proposed quality factors based on concepts, similar to Q_{NASA}, but depending only on measurements of LET (Borak et al., 2014).

As HZE ions penetrate shielding material they create a complex radiation environment inside habitats and spacecraft. The complexity of the radiation field is due to the fact that HZE ions experience nuclear (strong force) interactions with the nuclei of the target material. Nuclear interactions often produce secondary fragments that originate from the incident (projectile) or the target material. Le Tessa et al. found that 68% of a 1 GeV/nucleon iron beam has fragmented after 9.6 cm of aluminum (La Tessa et al., 2005).

The fluence rate of GCR is sufficiently low that coincident events within a large detector from the primary particles are rare, however secondary projectile fragments emerge from shielding with similar velocities and are grouped in space and time. Grouped particles that intercept a radiation detector simultaneously will register the sum of the energy deposition from each particle as opposed to the energy deposition of individual particles. A detection system must have the spatial resolution capable of identifying individual particles. This is driven by the fact that biological targets, with dimensions of a few microns, will be influenced by individual particles as opposed to the collection of clustered fragments from a single event measured in a detector with large lateral dimensions.

In practice, the spatial resolution of a detection system will be defined by the segmentation or pixelation of the detector e.g., a detector with a pixel size of 1 cm will also have a spatial resolution of 1 cm. In this paper, the spatial resolution required for detection systems was investigated with Monte Carlo methods using a subset of the GCR spectrum and various thicknesses of aluminum shielding. The radiation spectrum at several locations downstream of the target was then analyzed using a novel proximity method to determine the spatial resolution necessary to avoid coincident events and thus identify individual particles.

2. Materials and methods

2.1. Radiation transport methods

The Geant4 Monte Carlo toolkit, with its building block design, was chosen for this project (Agostinelli et al., 2003; Allison et al., 2006, 2016). With this software, detector experiments can be simulated virtually, without the use of expensive ground-based accelerator facilities. New detector designs can be screened and down selected in advance of expensive engineering and fabrication. This does not relax the requirements of the simulation procedures. Each component of the radiation transport computation and analysis methods must be carefully selected and well defined.

In Geant4, models that take into account specific physical interactions are defined and grouped into “lists” to cover a wide range of interactions types and energy ranges. Appropriate selection of the physics models is of great importance for accurate simulations. Based on the work by Ivantchenko et al. the QBBC physics list was chosen for these simulations (Ivantchenko et al., 2012). This physics list includes many different models and seeks high precision in many hadron-ion and ion-ion interactions over a wide energy range.

2.2. Geometric setup

Fig. 1 shows the geometrical configuration used for these studies. Spacecraft shielding is often composed of aluminum due to its strength and low specific gravity. Aluminum shielding, with areal densities of 5.4, 13.5, and 54 g/cm^2, were placed downstream from an ion beam directed at the center of the shield and normal to the surface. The coordinate system of the simulation was defined with the x and y dimensions of the system extending laterally and the positive z direction extending downstream. The origin of the simulation, ($x = 0$, $y = 0$, $z = 0$), is defined as the center of the backside (downstream plane) of the shielding. Positive z values start at the backside of the shielding, with respect to the location of primary ion generation, and extend downstream.

The detector system consisted of transparent (i.e., virtual) planes, placed at different distances downstream of the target. These virtual detectors registered the intersection of particles with the plane, but do not scatter these particles. The free space surrounding the shield and detector planes was the composition G4Galactic having a specific gravity of 1×10^{-25} g/cm^3 (Geant4). The lateral dimensions of each detector were large, 3 m, to ensure all fragments created intercepted the detection plane.

Primary particles incident upon the aluminum shielding can interact with the material. All surviving particles (primary and secondary) emerge downstream from the shielding. The position, direction, mass, charge and energy of all emerging particles are registered by each of the downstream detectors The stopping power in water and silicon, based on the Bethe-Bloch formalism, is also recorded as the particles intercept the virtual detector.

2.3. Incident ions

As discussed, galactic cosmic rays are composed of a broad range of ions and energies and can significantly increase the complexity of any simulations. For this study ^{4}He, ^{12}C, ^{14}Si and ^{26}Fe at energies of 300, 900 and 2400 MeV/n were generated and directed at the detector, normal to the surface. The motivation for selecting these ions was to limit the GCR spectrum to a few representative nuclei in order to identify possible trends with Z and still maintain a broad spectrum of fragments. These energies represent the approximate 25%, 50% and 75% quantiles of the GCR spectra as illustrated by the inverse cumulative energy distribution in Fig. 2. For this study, 36 million incident particles were simulated, i.e., 1 million particles for each combination of incident ion, energy and areal density combination.

The focus of this work was to look at the response of the detectors to incident primary particles and all fragments emerging from the target. For these studies, fragments were defined to be all ions from protons ($Z = 1$) to iron ($Z = 26$). Sparsely ionizing particles such as electrons, pions, and muons were tracked, but for simplicity were removed from the simulation output. Additional processing of the simulated output data was performed to filter the data set to include only particles with solid angle defined by cosine(θ) greater than 0.9, i.e. $\theta <$ 25 degrees. Filtering of data based on the z-directional cosine was done to represent a typical detector acceptance angle. Particles having a terminal range, after emerging from the shield, of less than 300 μm in silicon were also removed from the data set.

The stopping power of ions in silicon and water, for all emerging primary and secondary fragments intercepting the detector planes, was obtained from tables generated by the *emCalculator.ComputedTotalDEDX* function that is embedded in Geant4. These tables are based on the selected physics packages and material and use unrestricted stopping power.

2.4. Detector spatial resolution analysis methods

Galactic cosmic rays will intercept a spacecraft isotropically i.e., the fluence is considered to be uniform from all directions in space. However, GCR flux is sufficiently low that coincident events from separate incident primary ions can be assumed to be negligible for this work. Assessment of spatial resolution can then be reduced to the investigation of a single ion incident upon the shield and transporting this primary particle and all secondary particles through the shield and recording particle information and position at locations of the detector planes. All primary particles are normally incident upon the center of the upstream surface of the aluminum target.

It is possible to define a predetermined spatial resolution or