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Isotopic dependence of GCR fluence behind shielding

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Abstract

In this paper we consider the effects of the isotopic composition of the primary galactic cosmic rays (GCR), nuclear fragmentation cross sections, and isotopic-grid on the solution to transport models used for shielding studies. Satellite measurements are used to describe the isotopic composition of the GCR. For the nuclear interaction data-base and transport solution, we use the quantum multiple scattering theory of nuclear fragmentation (QMSFRG) and high-charge and energy (HZETRN) transport code, respectively. The QMSFRG model is shown to accurately describe existing fragmentation data including proper description of the odd–even effects as function of the iso-spin dependence on the projectile nucleus. The principle finding of this study is that large errors ($\pm 100\%$) will occur in the mass-fluence spectra when comparing transport models that use a complete isotopic-grid (~ 170 ions) to ones that use a reduced isotopic-grid, for example the 59 ion-grid used in the HZETRN code in the past; however, less significant errors ($< \pm 20\%$) occur in the elemental-fluence spectra. Because a complete isotopic-grid is readily handled on small computer workstations and is needed for several applications studying GCR propagation and scattering, it is recommended that they be used for future GCR studies.

Keywords: Space radiation shielding; Nuclear fragmentation; Galactic cosmic rays

1. Introduction

An important goal for NASA's Space Radiation Health Program is to develop a predictive capability to predict the GCR fluence spectra to within a $\pm 25\%$ accuracy (Anonymous, 1998). NASA has developed the HZETRN (high-charge and energy transport) code (Wilson, 1977; Wilson and Badavi, 1986; Wilson et al., 1991) as a science application and engineering design tool (Wilson et al., 1993) to be used in space radiation shielding studies. HZETRN has been validated in its ability to predict total dose and dose equivalent behind several materials in space to within $\pm 20\%$ on multiple space missions in Earth orbit (Cucinotta et al., 2000; Badhwar and Cucinotta, 2000; Badhwar et al., 2001). However, interest in fluence-based approaches to risk assessment (Cucinotta and Wilson, 1995; Cucinotta et al., 1996) suggests that more stringent tests of transport code accuracy be made, and the quantities dose and dose equivalent are deemed as necessary, but not sufficient tests of their accuracy. In this regard, we note that dose and dose equivalent are integral quantities that receive contributions from many GCR charge groups. There currently exist large uncertainties in biological response models for GCR (Cucinotta et al., 2001) and methodologies to estimate health risks such that dose and dose equivalent may be insufficient as tests of transport code accuracy. The use of ion fluence as a basis for tests for accuracy provides for sufficient generality to ensure accuracy in GCR transport models including under the circumstances of revision of radiation quality factors or integration of alternative risk assessment approaches in the future.

In the description of the transport of the galactic cosmic rays (GCR) in shielding materials or tissue, a common

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approximation is to consider only the elemental composition of the primary GCR and a reduced isotopic-grid for the secondary nuclei produced in nuclear fragmentation. In this paper we analyze the role of the isotopic dependence of the GCR primary composition and nuclear fragmentation in predicting the fluence of the GCR behind arbitrary shielding configurations. Our study is an important milestone in achieving NASA's goal of accurate GCR transport codes, since for the first-time a complete isotopic-grid has been achieved in a GCR transport model and we document the error inherent in former approaches. Also, for applications that will consider radioactive isotopes produced in the atmosphere or shielding, our study provides a useful tool to perform such analyses. Other applications where non-stable nuclei are considered are studies of the origin or the GCR where so-called cosmic-ray "clocks" consider the primary or secondary GCR with life-times on the order of confinement time in the galaxy (~ 1 M yrs) (Yanasak et al., 1999). Several GCR "clock" nuclei including ^{10}Be and ^{26}Al were not considered in the grid used in HZETRN in the past. Finally, new data on the GCR near Mars are being collected by the MARIE experiment on the Odyssey spacecraft (Zeitlin et al., 2004), and our study provides an opportunity to begin new investigations on the accuracy of computational models used to describe the GCR.

Historically the HZETRN code grew from a 29-ion isotopic grid used in the 1980s and early 1990s (Wilson et al., 1991) to an extension to a 32-ion isotopic grid made in 1993 in order to include all light ions (Cucinotta, 1993). Because of the limitations of random access memory present on the computer workstations of the early 1990s, sensitivity studies were made for mono-energetic ion beams to study the minimum number of isotopes for convergence resulting in the use of 59-isotopic grid (Kim et al., 1994), and all GCR studies since 1994 have used the 59-isotopic grid (Shinn et al., 1994). However, there are several reasons to re-consider the use of the full isotopic-grid for GCR transport problems. First, the isotopic dependence of the primary GCR has not been considered in past shielding studies and may lead to errors in the description of both primary ion attenuation and secondary particle production including the role of high-energy neutron production from the many neutron rich species that occur. Secondly, the studies of Kim et al. (1994) used the NUCFRG2 model of fragmentation (Wilson et al., 1994), which does not provide a correct description of the even–odd effect observed in fragment production or of the projectile iso-spin dependence observed experimentally (Knott et al., 1997; Zeitlin et al., 2001). Thirdly, the sensitivity studies made by Kim et al. (1994) used a "calibration" of the isotopic-grid to ^{56}Fe beams; however, a larger isotopic grid occurs when all GCR projectile nuclei are considered. Fourth, the error in the range energy and stopping powers that results from the use of a reduced isotopic grid, although expected to be small for large mass number, $A \gg 1$, is an unnecessary one for transport calculations. Finally, the improved computational speed and memory available on current small computer workstations, makes the inclusion of a complete isotopic-grid in the HZETRN code to be readily implemented at this time.

In this paper the implementation of the HZETRN code to include the full isotopic dependence of the primary GCR is described. The physics of isotopic effects in GCR transport are described and the fragmentation parameters are a key component of this description. The quantum multiple scattering theory of nuclear fragmentation (QMSFRG) is used as the generator for fragmentation cross sections used in our study. An empirical model of the isotopic composition of the primary GCR including its solar modulation is also described. For GCR problems an isotopic grid of 170 ions is identified and comparisons made to previous HZETRN results using the reduced-grid of 59 isotopes are made. The present code includes all of the abundant nuclei in the GCR environment with fluxes greater than about $10^2/\text{cm}^2/\text{yr}$ and nuclei produced in fragmentation events with production cross sections greater than about 1 mb. Several nuclei with smaller primary abundances or production cross sections, which are of interest for scientific reasons are also included in the expanded HZETRN model described herein. The resultant code includes many neutron rich nuclei that have been ignored in the past with iso-spin components ranging from $T_z = +3/2$ to $T_z = -3$.

2. Isotopic composition of the GCR

NASA currently uses the GCR model of Badhwar and O'Neill (1992) to describe the elemental composition and energy spectra of the GCR including their modulation by the sun's magnetic field. In this GCR representation, only the most abundant GCR nuclei is considered for each element and other isotopes of identical charge are counted as the abundant isotope. However, theoretical models and satellite measurements of the GCR have long considered the isotopic composition of the GCR and their modification through transport in interstellar space including estimating the primary nuclear composition at stellar sources (Parker, 1965; Webber et al., 1990a; Fields et al., 1994). The approach used here is to estimate an energy-independent isotopic fraction, f_j from satellite measurements, which are constrained to obey the sum rule

$$\phi(Z, E) = \sum_{A_j} f_j(A_j, Z)\phi(A_j, Z, E), \tag{1}$$

where the left-hand side of Eq. (1) is the elemental spectra from the Badhwar and O'Neill model and $\sum_j f_j = 1$. Eq. (1) is used herein as an initial estimate of the influence of the primary isotopic composition on GCR shielding calculations. Experimental studies have included measurements on the Pioneer, Voyager, and Ulysses spacecraft. A survey of such data (Hesse et al., 1991; Lukasiak et al., 1993, 1995; Webber et al., 1985, 1990a; Wiedenback and Greiner, 1981; Wiedenback, 1985) was made with the results shown in Table 1.

The GCR path-length distribution represents the mean amount of inter-stellar and inter-planetary material intersected by cosmic rays prior to their arrival in the near-Earth environment. This distribution is currently estimated to vary between 3 and $20\,\text{g/cm}^2$ with the inter-planetary gas approximately 90% H and 10% He. Variability in estimates between various