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Comparisons of fragmentation spectra using 1 GeV/amu ^{56}Fe data and the PHITS model

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Abstract

We present measurements and model calculations of fluence and linear energy transfer in water (LET_∞) obtained using ^{56}Fe beams with 1 GeV/amu kinetic energy incident on aluminum, polyethylene, PMMA, and lead targets. The measured spectra are compared to predictions of the PHITS model. The study is motivated by NASA's need to develop accurate heavy ion transport codes to assess radiation exposures in deep space, where galactic cosmic rays are important. The data were obtained at the Alternating Gradient Synchrotron at the Brookhaven National Laboratory. Distributions of charge and LET depend on the depth and composition of the target. Several of the targets studied are "thick", defined operationally as a depth that presents at least 50% of an interaction length to the beam ions. In a thick target, the probability of a secondary interaction is significant, tertiary interactions can also be important, and the target-exit fluence and charge distributions depend on unmeasured cross sections that can only be estimated by nuclear interaction models. Comparisons between calculated and measured spectra are therefore of considerable interest. Some targets used in the study are thin, so that secondary and higher interaction probabilities are negligible, allowing more stringent comparisons between the data and the model. We find that PHITS reproduces some aspects of the experimental data well, but fails to accurately reproduce many of the measured fragment fluences.

Keywords: Galactic cosmic rays; Heavy ions; Shielding; Fragmentation; PHITS; Models; Monte Carlo

1. Introduction

1.1. Galactic cosmic ray simulation

The space radiation environment is complex and varies both with time and location. In deep space, or in high-inclination low-Earth orbit, one of the major sources of radiation dose, and especially dose equivalent, is protracted exposure to the galactic cosmic rays (GCR). The GCR present a relatively steady flux of energetic ions, many of which can penetrate tens of g cm^{-2} of matter, and some of which have high LET. (We refer throughout to linear energy transfer, or LET, in water. This is unrestricted LET, i.e., in an infinite volume, sometimes written as LET_∞.) Substantial percentages of the dose and dose equivalent received in unshielded deep space come from highly ionizing nuclei such as Si and Fe (Lin, 2007). These high-LET particles can cause biological effects that are considerably different from those caused by the various types of radiation found on the surface of the Earth (NCRP, 2007). For astronauts in deep space, chronic exposure to a low-dose-rate of heavy ions is inevitable, though the details of the exposures will vary substantially with shielding conditions. Because the biological response to mixed-field exposures including heavy ions is not well understood, NASA is conducting extensive research in heavy ion radiobiology (Lowenstein and Rusek, 2007). On the physics side of the problem, efforts such as the work presented here are being made to improve heavy ion transport models. Though we focus here on a single ion species and energy, we have shown in recent work (Guetersloh et al., 2006) that the dose reduction results obtained at this energy are representative of results for all high-energy heavy ions in the GCR.

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Table 1
Properties of elemental and polymer target materials

Material	σ_{cc} (mb)	λ (g cm^{-2})	Range (g cm^{-2})	$E(R = 5\,\mathrm{g\,cm^{-2}})$ (MeV/amu)	Fe survival $P(5\,\mathrm{g\,cm^{-2}})$
H (liquid)	661 ± 23	2.5 ± 0.1	13.2	525	0.137 ± 0.009
Be	1490 ± 17	10.0 ± 0.1	18.1	291	0.607 ± 0.003
C	1537 ± 15	13.0 ± 0.1	30.3	308	0.680 ± 0.003
Al	2010 ± 50	22.3 ± 0.6	34.0	284	0.799 ± 0.004
Cu	2789 ± 70	38.1 ± 1.0	40.0	258	0.877 ± 0.003
Pb	4554 ± 133	75.4 ± 2.2	54.5	218	0.936 ± 0.002
CH_2	2859 ± 44	8.1 ± 0.1	27.2	343	0.541 ± 0.005
$C_5O_2H_8$	16600 ± 200	10.0 ± 0.1	29.5	326	0.606 ± 0.004

1.2. High-energy iron: fragmentation and energy loss

According to the GCR model developed by Badhwar and O'Neill (1992), in unshielded free space in the inner heliosphere, iron ions deliver about 8% of the total dose from the GCR and 27% of the dose equivalent at times near solar maximum, even though they contribute less than 1% of the total GCR flux. The large dose and dose equivalent contributions are due to two factors: first, that iron, with charge 26, has the highest charge, Z, and LET of any relatively abundant GCR ion; and, second, because high-energy iron has LET on the order of 150 keV/μm, it is near the peak value of the quality factor as defined by the ICRP (1991). Behind shielding, iron fragmentation cross sections (Zeitlin et al., 1997) determine the probabilities for producing other, lighter species in nuclear interactions. These interactions play a large role in determining the shielding effectiveness of various materials. Measured charge-changing cross sections and interaction lengths, λ, for energetic Fe are shown in Table 1; the data are reasonably well fit by a power-law, going as $\lambda\ (\mathrm{g\,cm^{-2}}) = 2.54A^{0.645}$, where A is the mass number of the target material. These values are expected, for targets other than hydrogen, to be only weakly dependent on energy, since the underlying cross sections have weak energy dependence. (The charge-changing cross section for ^{56}Fe on H increases by about 50% as the beam energy increases from 400 to 5000 MeV/amu. In contrast, charge-changing cross sections on C, Al, and Cu targets are approximately energy-independent in this range.) Table 1 also shows the calculated range of a ^{56}Fe ion with 1 GeV/amu kinetic energy in each material. Like interaction length, range (given here in g cm^{-2}) increases with increasing target mass number, though not as sharply as λ. Ranges as a function of target mass number are also fairly well fit by a power-law relation, with $R(\mathrm{g\,cm^{-2}}) \approx 12.8A^{0.275}$. Since, as we will explain below, nuclear interactions that cause fragmentation tend to reduce dose, the relatively rapid increase of mean free path with target A (taken together with the comparatively weak A dependence in the range-energy relation) means that the interaction probabilities—and hence shielding effectiveness—decrease fairly rapidly with increasing target mass number.

Note that the charge-changing cross section for Pb shown in Table 1 is about 9% higher than that reported earlier (Zeitlin et al., 1997). Subsequent to that publication, an error in the target areal density was discovered. Also, additional Pb-target data have been obtained that—combined with the revised analysis of the older data—yield the higher cross section. The carbon-target charge-changing cross section is also higher than previously reported (Zeitlin et al., 1997), by about 2.7%. This is very slightly beyond the quoted one-sigma uncertainty; the change is in this case due to the addition of newer data sets and a slightly revised analysis of the older data.

In any application involving charged particles, shielding efficiency is enhanced by stopping as many incident particles as possible by means of ionization energy loss ($\mathrm{d}E/\mathrm{d}x$). However, most GCR particles cannot be stopped in modest shielding depths, and those that survive traversal of the shield without fragmentation are slowed and hence shifted to higher LET, so that in many cases they are more biologically damaging than they would have been in the absence of the shield. To further emphasize this point, we show in Table 1, in the 5th column from the left, the energy in MeV/amu required for a ^{56}Fe ion to penetrate a 5 g cm^{-2} depth of each material. The energy distribution of GCR Fe has a broad peak in the region of 300–600 MeV/amu, and the advantage of hydrogen is clear, as 5 g cm^{-2} would stop much more of the flux than would the same areal density of any other material. Thus polymers such as polyethylene (CH_2) and polymethylmethacrylate (known by the acronym PMMA, with chemical formula $C_5O_2H_8$) are of interest as shielding materials.

A specific example may be useful in understanding the differences between materials and the relative importance of energy loss vs. fragmentation. We consider a depth of shielding equal to 5 g cm^{-2}, and a ^{56}Fe ion with 500 MeV/amu kinetic energy incident up on it; such a particle cannot penetrate the hydrogen shield, but would penetrate all others. In the hydrogen shield, the ion would come to rest after traversing 4.7 g cm^{-2}, but this is not a likely outcome—it is far more likely (85% probable) to interact before stopping. Thus the transmission of the hydrogen shield would be either nothing, or a lighter ion or ions, and the dose received behind the hydrogen would be reduced compared to the dose incident on the shield. (In some cases, a lighter ion produced in the shield could have a larger $Q(L)$ than the incident ^{56}Fe ion did. However, on average both dose and dose equivalent would be reduced by the shield.) In contrast, for a shield consisting of 5 g cm^{-2} of Be, the iron ion would penetrate most of the time, with $a \sim 61\%$ probability of surviving without undergoing a charge-changing interaction. (For a fixed areal density, the probability for survival increases as