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Polyethylene as a radiation shielding standard in simulated cosmic-ray environments

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Abstract

Radiation risk management for human space missions depends on accurate modeling of high-energy heavy ion transport in matter. The process of nuclear fragmentation can play a key role in reducing both the physical dose and the biological effectiveness of the radiation encountered in deep space. Hydrogenous materials and light elements are expected to be more effective shields against the deleterious effects of galactic cosmic rays (GCR) than aluminum, which is used in current spacecraft hulls. NASA has chosen polyethylene, CH_2, as the reference material for accelerator-based radiation testing of multi-function composites that are currently being developed. A detailed discussion of the shielding properties of polyethylene under a variety of relevant experimental conditions is presented, along with Monte Carlo simulations of the experiments and other Monte Carlo calculations in which the entire GCR flux is simulated. The Monte Carlo results are compared to the accelerator data and we assess the usefulness of 1 GeV/amu ^{56}Fe as a proxy for GCR heavy ions. We conclude that additional accelerator-based measurements with higher beam energies would be useful.

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1. Introduction

Much of the motivation for this work is derived from the NASA Space Radiation Health Program [1]. Finding effective approaches to shielding against radiation is one of the highest priority issues. The scope of the risks associated with the health, safety and performance of crews exposed to ionizing radiation during space flight have been identified previously [2]. Here, we focus on the particular importance of polyethylene as a reference material for laboratory tests of shielding materials. For most of the particles and energies found in the galactic cosmic ray (GCR) spectrum, the effectiveness of a material as a radiation shield generally increases with decreasing atomic number, with hydrogen being the best [3,4], as described in detail in the accompanying paper [5], in which many materials were tested in a beam of 1 GeV/amu ^{56}Fe ions at the Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS). Since hydrogen is highly effective, one would expect polyethylene, CH_2, with two hydrogen atoms and one carbon atom per molecule, to also be an effective shielding material, and in fact blocks of it have been added to the crew sleeping quarters on the International Space Station to provide radiation protection [6,7]. Furthermore, polyethylene is readily available, non-toxic and chemically stable under typical conditions, making it

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a convenient reference material for shielding tests at heavy-ion accelerators. NASA materials scientists are developing new composites as they seek to create materials that have both high hydrogen content and sufficient tensile strength to serve as structural members in spacecraft. For each target supplied to us for testing in heavy-ion beams, a CH_2 target with equal areal density was also supplied, and the CH_2 results were used as the standard to which the other materials were compared. As we will show, these comparisons appear to be a reasonable approach for judging the effectiveness of materials against high-energy beams (600 MeV/amu and higher), but perhaps not meaningful at the lower energies.

Hydrogen is of particular interest for studies of GCR propagation through interstellar space, and also as a component of spacecraft shielding. Accordingly, we have measured nuclear cross sections for many beam ions and energies incident on hydrogen targets [8–12]. The fabrication and use of liquid hydrogen targets are problematic, so as a practical matter the required data are most easily obtained by making cross section measurements for both polyethylene and carbon targets. In the data analysis, carbon-target cross sections are subtracted from the polyethylene results, yielding hydrogen-target cross sections. As a byproduct of these efforts, there are a considerable number of ion/energy combinations for which we have obtained data using the same 2.83 g cm^{-2} polyethylene target. By using the same target for a wide variety of beams, we are able to describe for the first time the systematic dependencies of shield performance on ion species and energy for GCR-like particles. Taken as a whole, our experimental data can be considered a simulation of highly-relevant portions of the GCR spectrum. In addition, we have simulated the shielding properties of polyethylene against the full GCR spectrum using a Monte Carlo computer code, described below.

Although we have obtained data for several ions and energies, our focus to date has been on the portion of the energy spectrum below 1 GeV/amu. This is a necessary, but not sufficient, set of measurements. As we will show, data at higher energies are needed to complete our understanding of the shielding properties of polyethylene and other materials.

2. Materials and methods

2.1. Experimental setup

A particle spectrometer made of a stack of silicon detectors was used for all measurements; our experimental methods [13] and data analysis techniques [8–11] have been described elsewhere. A typical beamline configuration as used at the Heavy Ion Medical Accelerator in Chiba (HIMAC, located at the National Institute of Radiological Science in Japan) is shown schematically in Fig. 1. Most of the data presented here are from experiments performed at HIMAC; the rest are from the Brookhaven AGS and NSRL accelerators. For most of the experiments, a small (50 mm^2 active area) silicon detector, referred to as TR, was mounted in the most upstream location to initiate the experimental trigger and to define the beam area. A 3 mm thick silicon detector, labeled d3mmU in Fig. 1, was placed just downstream of TR and was used in the off-line analysis to resolve the species of the particles emerging from the vacuum line and entering the target based on the deposited energy, ΔE, in the detector. This detector, and all other 3 mm thick detectors used here, are lithium-drifted and have active radii of 1.15 cm. In the offline data analysis, cuts are made so that our sample consists only of events in which a single ion of the accelerated beam species was recorded in both TR and d3mmU. In a small number of the experiments reported here (those performed at the AGS and NSRL), it is conceivable that some contamination of our spectra arises from beam particles outside the radius of d3mmU; however, as discussed in detail in the Appendix, we expect this source of contamination to be negligible.

Polyethylene targets were placed downstream of d3mmU. Downstream of the target position, two 3 mm thick silicon detectors record fragments and surviving primary ions emerging from the target. Immediately downstream of this pair was a pair of silicon position-sensitive detectors (PSDs). These have active radii of 2.0 cm and thicknesses of 800–1050 μm. The PSDs provide spatial resolution and species identification, though typically with less ΔE resolution than the 3 mm detectors. Because the first pair of 3 mm detectors and the PSD pair were placed near the target exit, they subtend relatively large angles of acceptance, which is appropriate for our measurements of charge-changing cross sections. An unavoidable consequence of this close placement, however, is the loss of apparent resolution in the spectra below about half the beam charge ($Z_{beam}/2$). This effect is not due to any degradation of the detector response, but to the presence, in some events, of multiple light fragments exiting the target and striking the detectors simultaneously.

A pair of 5 mm thick silicon detectors (d5mm1 and d5mm2) and a second pair of 3 mm thick detectors (d3mm3 and d3mm4) were mounted downstream of the second PSD to provide high-resolution particle identification of ions at small acceptances. The 5 mm detectors have active radii of about 1.95 cm, nearly double that of the 3 mm detectors. These far-downstream detectors were typically placed about 1–1.5 m behind the target. Since these detectors subtend smaller acceptance angles and are typically hit by a lower multiplicity of fragments on a given event, they can be used to identify the most forward-going fragment(s) in these events. See [5] for a comparison of the spectra seen with detectors having large and small acceptances.

The data reported here were obtained with seven beam energies. We refer to the beam energy at extraction from the accelerator; actual energies at the target were slightly lower due to energy lost in the detectors upstream of the target. The extraction energies are 290, 400, 600, 650, 800, 1000 and 1200 MeV/amu. In the interests of simplic-