Shielding experiments with high-energy heavy ions for spaceflight applications

C Zeitlin\textsuperscript{1,5}, S Guetersloh\textsuperscript{1}, L Heilbronn\textsuperscript{1}, J Miller\textsuperscript{1}, N Elkhayari\textsuperscript{2}, A Empl\textsuperscript{2}, M LeBourgeois\textsuperscript{2}, B W Mayes\textsuperscript{2}, L Pinsky\textsuperscript{2}, M Christl\textsuperscript{3} and E Kuznetsov\textsuperscript{4}

\textsuperscript{1} Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
\textsuperscript{2} Physics Department, University of Houston, Houston, TX, USA
\textsuperscript{3} NASA Marshall Spaceflight Center, Huntsville, AL, USA
\textsuperscript{4} Physics Department, University of Alabama, Huntsville, AL, USA
E-mail: cjzeitlin@lbl.gov

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Abstract. Mitigation of radiation exposures received by astronauts on deep-space missions must be considered in the design of future spacecraft. The galactic cosmic rays (GCR) include high-energy heavy ions, many of which have ranges that exceed the depth of shielding that can be launched in realistic scenarios. Some of these ions are highly ionizing (producing a high dose per particle) and for some biological endpoints are more damaging per unit dose than sparsely ionizing radiation. The principal physical mechanism by which the dose and dose equivalent delivered by these particles can be reduced is nuclear fragmentation, the result of inelastic collisions between nuclei in the hull of the spacecraft and/or other materials. These interactions break the incident ions into lighter, less ionizing and less biologically effective particles. We have previously reported the tests of shielding effectiveness using many materials in a 1 GeV nucleon\textsuperscript{−1} \textsuperscript{56}Fe beam, and also reported results using a single polyethylene (CH\textsubscript{2}) target in a variety of beam ions and energies up to 1 GeV nucleon\textsuperscript{−1}. An important, but tentative, conclusion of those studies was that the average behavior of heavy ions in the GCR would be better simulated by heavy beams at energies above 1 GeV nucleon\textsuperscript{−1}. Following up on that work, we report new results using beams of \textsuperscript{12}C, \textsuperscript{28}Si and \textsuperscript{56}Fe, each at three energies, 3, 5 and 10 GeV nucleon\textsuperscript{−1}, on carbon, polyethylene, aluminium and iron targets.

Author to whom any correspondence should be addressed.
1. Introduction

High-energy heavy ions in galactic cosmic rays (GCR) contribute substantially to the dose and dose equivalent in deep space [1]. Because the dose rate from GCR is low, on the order of a few hundred microGray per day, the GCR are not a major concern for short missions such as those undertaken in the Apollo era. However, when future missions take astronauts to the lunar surface for extended periods of time, and possibly to more distant destinations for even longer periods, radiation exposure will be a major concern. Although one cannot reproduce the full complexity of the GCR in the laboratory, we can nonetheless gain valuable insights into the issue of shielding against the GCR by studying representative high-energy heavy ions produced at accelerator facilities. The data presented here come from an experiment performed at the Brookhaven National Laboratory’s alternating gradient synchrotron (AGS) in July 2005 using beams of $^{12}$C, $^{28}$Si and $^{56}$Fe, with each ion species measured at three energy points, 3, 5 and 10 GeV nucleon$^{-1}$. Previously reported data also came from the AGS as well as the NASA Space Radiation Laboratory (also at Brookhaven) and the Heavy Ion Medical Accelerator at Chiba (HIMAC) at the National Institute of Radiological Sciences in Japan. The July 2005 experiment differed in a few important respects from our other experiments (see e.g. [2]–[5]), as described below. Some of these modifications, in particular the increased complexity of the experimental trigger, complicate the data analysis. Nonetheless, we are able to present results that are directly comparable with our previous work in this area [6, 7].

Important theoretical work by Wilson et al [8] regarding the shielding effectiveness of different materials was substantially verified in a series of ground-based experiments performed by our group. In [6], we showed that, as expected from the calculations in [8], hydrogen produces the greatest dose reduction per unit areal density of any shielding material for 1 GeV nucleon$^{-1}$ $^{56}$Fe ions. As the mass number of the target nucleus increases, shielding effectiveness per unit mass decreases, also as predicted. In [7], we explored the energy and...
beam-ion dependences of our shielding results, and using our Monte Carlo simulation of the GCR, concluded that while $^{56}$Fe with a kinetic energy of 1 GeV nucleon$^{-1}$ gave a reasonable representation of the GCR, beams with higher energies would be better proxies for the average behavior of heavy ions in the GCR. The choice of beam ion was found to be less important than the choice of beam energy for this purpose, at least for ions above nitrogen in the periodic chart. This behavior is summarized by the data in figure 1.

The reduction in dose and dose equivalent that can be achieved by a careful choice of shielding may be significant in mission planning. Ideally, the hull of a spacecraft would also provide good shielding against GCR, but to date all spacecraft hulls have been made of aluminium alloys, and—as previous work shows—aluminium is far from optimal for radiation protection purposes. Also, as shown in [6], the shielding effectiveness of any material depends on the depth and composition of shielding that precedes it, as we will explain in more detail below.

A given depth of material produces the greatest reductions in dose at its entrance, and the dose reduction decreases exponentially. Consequently, the advantage gained in going from, say, 20 g cm$^{-2}$ of shielding to 25 g cm$^{-2}$ is considerably less than that gained in going from 10 to 15 g cm$^{-2}$. In addition, the data suggest that the ordering of shielding materials is important: hydrogenous materials have the greatest benefit if they are in the outermost layer of shielding. If they are deployed inside an already well-shielded area, their advantage over other materials is reduced. These conclusions were reached with the 1 GeV nucleon$^{-1}$ $^{56}$Fe beam; the present data sets do not allow us to test the depth dependence of the materials, since only one target depth was used per beam. However, Monte Carlo calculations can be used to explore this aspect of shield performance.
2. Summary of previous results

In our previous studies [6, 7], we defined \( \delta D_n \), the change in dose per incident beam ion, normalized (hence the subscript ‘\( n \)’) to the depth of the target in units of grams per square centimetre. For the planar geometry of our experiments, in which we always detect at least one charged particle emerging from the target for every incident primary ion, it is straightforward to show that the dose delivered by the mix of fragments and surviving primary ions (i.e. those that did not undergo a charge-changing nuclear interaction in the shield) that emerge from a shield is proportional to the average linear energy transfer (LET) of the particles that make up the distribution. (We refer throughout to LET in water, in an infinite volume so that all ionization electrons are included, even high-energy delta-rays.) Similarly, the dose due to the primary beam ions is proportional to their LET, taken to have a single value. Thus the change in dose per unit areal density of the target can be written as

\[
\delta D_n = (L_{\text{track}} - L_{\text{primary}})/(L_{\text{primary}} \times \rho d)
\]

where \( L_{\text{track}} \) is the simple average of LET of the particles exiting the target, \( L_{\text{primary}} \) is the LET of the primary ion, \( \rho \) is the density of the shield in grams per cubic centimetre and \( d \) its depth in centimetres. Thus \( \delta D_n \) has units of \( (\text{g cm}^{-2})^{-1} \).

Driven by the fact that the number of surviving primaries at depth \( x \) is given by \( e^{-x/\lambda} \), where \( \lambda \) is the interaction mean free path, the shielding effectiveness as measured by \( \delta D_n \) also decreases exponentially with depth [6]. Since targets of differing depths were used in the course of the many experiments reported, when an adequate number of data points was available, we extracted the parameter \( \delta D_0 \) by fitting measured points according to

\[
\delta D_n(x) = \delta D_0 e^{-bx}
\]

The quantity of interest when comparing different target materials is actually \( \delta D_0 \), since it is independent of the depths of the targets used. It represents the ‘initial’ shielding effectiveness of a particular material. As shield depth increases, all materials become less effective, and the greatest benefit in terms of dose reduction will be gained from putting the most effective material or materials first (i.e. as the outermost layer of a multi-layer spacecraft hull).

In [7], we studied the \( \delta D_n \) produced by a single target, 2.824 g cm\(^{-2}\) of polyethylene (CH\(_2\)) in many different beams, ranging from \(^{12}\)C to \(^{56}\)Fe, at energies from 290 MeV nucleon\(^{-1}\) to 1 GeV nucleon\(^{-1}\). An important result of the study is shown in figure 1; it shows that, for beam energies of 600 MeV nucleon\(^{-1}\) and higher, \( \delta D_n \) is only weakly dependent on the ion species, for ions of charge 8 (O) and above. This is a potentially useful result: the GCR contain a mix of ions, and this plot suggests that studying any one species at a particular energy is sufficient. We revisit that tentative conclusion here. Also, while \( \delta D_n \) appears to be approximately independent of the beam ion, it does depend strongly on the beam energy. And although the largest dose reduction was found when the target was placed in the 1 GeV nucleon\(^{-1}\) \(^{56}\)Fe beam, it corresponds to a rather modest \( \delta D_n \) of 4.7\% (g cm\(^{-2}\))\(^{-1}\), whereas our Monte Carlo simulation of the GCR heavy ions in CH\(_2\) yielded a \( \delta D_n \) of about 7\% (g cm\(^{-2}\))\(^{-1}\). For reasons explained below, we now believe this estimate to have been too high, and that a more realistic simulation would yield \( \delta D_n \) in the range of 6–6.5\% (g cm\(^{-2}\))\(^{-1}\).
3. Experimental configuration

The experiment performed at the AGS in 2005 was similar to (but with a few significant differences from) others performed by our group. Our usual experimental set-up and data analysis methods have been described in [2]–[5]. Usually, we place several silicon detectors in pairs in two or three locations downstream of the target, with an additional pair in front of the target. All detectors are read out by standard electronics, including charge-sensitive preamplifiers, shaping amplifiers, and analog-to-digital converters. The detectors record energy deposition, $\Delta E$, from charged particles that pass through them. The detectors upstream of the target are used for triggering (we trigger on every incident primary ion) and allow us, in the off-line analysis, to select events in which one and only one well-identified primary ion was incident on the target. The detectors downstream of the target are typically arranged so that the pair closest to the target subtends a cone with a half-angle in the range from $5^\circ$ to $10^\circ$. These ‘large acceptance’ detectors are used to identify primaries that survive traversal of the target, and fragments with charge $Z$ down to about half the charge of the beam species.

Below about $Z_{\text{beam}}/2$, large-acceptance spectra lose resolution, not due to any defect of the detectors, but because of the relatively high multiplicity of fragments that are produced in the more central collisions that populate this part of the spectrum. The energy deposition in the silicon detectors is proportional to the sum of the square of the charges of the individual fragments that hit the detector on a given event. In the well-resolved portion of the spectrum, the sum is dominated by a single fragment. In the unresolved portion of the spectrum, the many different combinations of fragments yield a continuum of $\Delta E$ values rather than distinct peaks.

In typical experiments, we do not measure particles more than a few degrees off the central axis of the beam, and because readout times are relatively long (on the order of 150 $\mu$s), we keep beam currents low, with about 500 primary ions incident on the upstream detectors per spill (typically about 0.5 s in length). In the experiment described here, a different approach was taken. A high priority was to measure, using other detector systems, projectile fragments and other particles, both charged and neutral, at angles significantly off the beam axis. Figure 2 is a schematic diagram of the beamline configuration. The off-axis systems included the Zero-Degree Detector System (ZDDS) provided by NASA Marshall Spaceflight Center (MSFC), which is a matrix of solid state detectors; a silicon strip detector system provided by the University of Houston group; and a set of four neutron detectors provided by MSFC and configured by the LBNL group. Three separate readout systems were used, one for the on-axis and neutron detectors, one for ZDDS, and one for the UH strip detectors. Data were merged off-line by the UH group and analyzed using information from all subsystems, but the results of that analysis are not discussed here.

To attain reasonable rates in the off-axis systems, the beam current was about 5000 primaries/spill. The beams were approximately 1 cm in diameter (FWHM) with a momentum spread $\delta p/p$ of about 2%. To avoid damaging the silicon detectors, and to make sure the trigger was sufficiently fast, the usual upstream silicon detectors were replaced by a single plastic scintillator, of dimension $1 \text{ cm} \times 1 \text{ cm} \times 1.8 \text{ mm}$; this is referred to as ‘TP’, for trigger plastic. As the off-axis data were the priority, we minimized the detector mass near the target, since the mass of those detectors acts as a second target. These considerations led us to sacrifice resolution in the on-axis detectors. A second plastic scintillator (P2, with dimensions of $3 \text{ cm}$ square by $1.8 \text{ mm}$ thick) was placed immediately downstream of the target, and a pair of $300 \mu\text{m}$ thick detectors from Ortec was used as the large acceptance particle identifier. (There is no particular
Figure 2. Schematic diagram of the detectors on and off the beam axis. Beam is incident from the left. Plastic scintillators TP and P2 were placed close to the target on either side, followed by one or two silicon detectors (two are shown) and a third plastic scintillator, P3. Charged particles at angles greater than about 3° were detected by the University of Houston’s silicon strip system and/or the MSFC’s ZDDS. Four neutron detectors were also placed at various angles with respect to the beam axis, but they would be outside the boundaries of the diagram.

significance to the depth of TP or P2; they were chosen because they were readily available and not so thick as to cause significant fragmentation of the beam before it reached the target.) Due to the relatively high beam currents and the high LET of the beam particles, fairly rapid degradation of the Ortec detectors was observed, particularly in the $^{56}$Fe beams. With a limited number of spare detectors on hand and the many beams to be run, it was not feasible to run with a pair of silicon detectors for much of the experiment. (That is, the detectors were failing at a rate that would have left us with no working units about two-thirds of the way through.) Thus, for most of the datasets, we must rely on the combination of P2 and one silicon detector for event selection and particle identification. The resolution obtained with these detectors is much worse than in our other datasets, but is adequate for present purposes.

An additional plastic scintillator, P3, with the same dimensions as P2, was placed far downstream of the target. This detector, with its small acceptance, is hit by the most forward-going particle in the event. Primaries and heavy fragments have very forward-peaked angular distributions, but the distributions broaden as fragment mass decreases. Thus a small-acceptance detector sees a much lower multiplicity of particles than a large-acceptance detector, and this results in good resolution at the low end of the $\Delta E$ distribution. We note that, as is typical of plastic scintillators, the responses of both P2 and P3 are quite nonlinear with $\Delta E$; there is obvious quenching on large deposition events. This, and the relatively poor resolution of...
these detectors, complicates both particle identification and measurement of LET, and so for the analysis presented here, we rely entirely on the large-acceptance silicon detector(s). The off-axis data from this experiment will be presented elsewhere. Here, we are only concerned with the distributions of forward-going primaries and fragments that emerge from the target, and the information these distributions contain with regard to shielding against GCR.

3.1. Triggering

A trigger was developed that improved the efficiency of collection of data from the off-axis detectors compared to our normal method. Typically, the trigger is simply a coincidence of hits above the thresholds (which are set so that only the primary ion signals are above it) in the detectors upstream of the target. Here that would have meant triggering exclusively on TP, and with the high beam current, we would have had extremely high dead time and poor statistics in the off-axis systems. Rather than eliminating the TP trigger, it was decided to prescale it, that is, to accept only a fraction of them. A prescaling module made it possible to reduce the TP rate in steps of 4, that is, by a factor of 4, 16, etc. Most of the data were taken with the prescale factor set to 4.

Other triggers indicated hits in the off-axis detectors. The master trigger for the experiment was a logical OR of the prescaled TP trigger and the (not prescaled) off-axis triggers. Thus, the latter triggers fired the trigger logic 100% of the time, whereas only one-in-four or one-in-sixteen TP triggers did so. The overall rate was greatly reduced compared to a TP-only trigger, and this kept the dead time at an acceptable level, usually around 50%. While this scheme was necessary to accommodate the off-axis systems, it altered the spectra obtained in the on-axis detectors—the measured distributions are biased against the majority of events, which contain either surviving primaries or a small multiplicity of very forward-produced fragments. The latter category includes events in which a peripheral interaction occurred and the leading fragment is within a few charge units of the primary. The biases must be removed in the data analysis; this requires knowledge of the trigger for each event. That information is made available by setting and reading out on every event, a ‘latch register’ module. Each logic-high signal sets a bit in the register, corresponding to a data value that is part of the event record. The prescaled TP trigger was assigned to bit 1 of the register, and the off-axis detectors were assigned bits 3 and 4. All combinations of set bits are possible. Thus a register reading (referred to as a latch value) of 1 means that only TP fired; a value of 8 or 16 indicates that the trigger for the ZDDS system or neutron system, respectively, fired. A value of 9 is due to a coincidence of prescaled TP and ZDDS, 17 to prescaled TP in coincidence with one of the neutron detectors, etc. For data analysis purposes, it is only necessary to know whether the latch value was 1, or whether it was 8 or higher.

4. Data analysis

The data were analyzed to obtain charge-changing and fragment production cross sections \[9\], as in previous work. This involves counting events in bins corresponding to the charge of the particle(s) seen in the large-acceptance detectors. This is generally possible only for surviving primaries and for fragments with charge \(Z\) greater than about half that of the beam. In some of these data, even fewer fragment species can be resolved, because the high beam energies produce high multiplicities of fragments with very strongly forward-peaked angular
distributions. (The angular distributions as seen in the laboratory frame depend strongly on the forward boost, i.e. the $\beta\gamma$ of the fragments, which is approximately equal to that of the primary. This is much larger in these data than in our previous experiments.) In the analysis, we select events in which the pulse height signal from TP was consistent with one and only one primary ion. Even so, when we run the experiment with no target (as is always done at least for one data set, for each beam ion/energy combination), some fragments are seen in the detectors downstream of the target position. These are produced in interactions of beam ions in the air gaps between TP and P2, and P2 and the silicon detector, or in the detectors themselves. Some of these events can be removed by requiring a good correlation of signals between P2 and the silicon detector, or between the two silicon detectors when two were present, but there are always some fragmentation events seen even without a target. The same interactions presumably occur when a target is present, so the target-out data are used to estimate the efficiency for detecting primaries and to subtract the fluences of fragments produced in places other than the target. Additional corrections are applied to account for particles lost due to interactions in the detectors, which occur with a species-dependent probability. In the cross section analysis, we also account for secondary interactions in the target; however, in this analysis, we wish to include the effects of the secondary interactions, so those corrections are not applied.

In [6], we discussed two methods of determining the average LET of a distribution of particles emerging from a target. The first method is simpler and uses only the change in the average $\Delta E$ in silicon when a target is placed in the beam compared to the target-out average $\Delta E$. The second method involves using most of the steps of the cross-sectional analysis to obtain the charge distribution, and then assigning each charge an average LET based on the measured LET of the primary and scaling by $Z^2$. We showed in [6] that the two methods gave results that agreed within a few percent of each other, a precision better than is needed here. Because the data have been analyzed for cross sections, and the somewhat complicated procedure to correct for trigger bias was necessary for that analysis, the second method of obtaining average LET was used here.

4.1. Charge identification

Figure 3 shows typical histograms of pulse height (proportional to $\Delta E$) obtained at large acceptance with, respectively, the 5 GeV nucleon$^{-1}$ $^{56}$Fe beam, the 10 GeV nucleon$^{-1}$ $^{28}$Si beam, and the 3 GeV nucleon$^{-1}$ $^{12}$C beam. These and similar histograms can be rescaled to produce charge histograms, an example of which is shown in figure 4. This plot is created by histogramming the square root of $\Delta E$ multiplied by an appropriate scale factor. The method does not account for the fact that the signals in the silicon detectors are actually proportional to the sum of the squares of the fragment charges, i.e. $\sum_i Z_i^2$, where the index $i$ runs over all particles within the detector acceptance. As a result, the contributions of non-leading fragments are increasingly significant as the $Z$ of the leading fragment decreases. In the charge histograms, this is manifested by a shift of the fragment peaks to values higher than they would be if only the leading fragment were recorded.

Based on the charge histograms, events are counted and recorded in a spreadsheet as a function of charge. The corrections described above are applied, and a pseudo fluence, $\phi$ versus $Z$ spectrum, normalized to the total corrected number of particles, is obtained. (This is actually the probability distribution for detecting a particle of charge $Z$ exiting from the target, given one beam ion entering the target. It is not a proper fluence because we treat the recorded $\Delta E$
Figure 3. Pulse height spectra for the beams and targets indicated in the individual histograms. The large peaks due to the detection of surviving primary ions have been suppressed to better display the fragment peaks. The histograms are uncorrected for the trigger bias and other smaller effects that require corrections. In the carbon beam data, only two significant peaks are seen, one for boron fragments (charge 5, to the right), and the other, much larger peak of unresolved events. The very small peak near ADC channel number 45 may correspond to detection of a single proton.

signals as if they were due to a single particle, and also because the area of the detectors is not 1 cm$^2$.) Figure 5 shows, as the gray bar chart, the $\phi$ versus $Z$ spectrum before corrections, in bins 1 charge unit wide, corresponding to the entries in the spreadsheet. Events below charge 12, where there is no charge resolution due to the high fragment multiplicities, are added together at the value (in the case of figure 4, $Z = 6.6$) that corresponds to the average $\Delta E$ of those events.

4.2. Event weighting to compensate for trigger bias

The data represented by the gray bars in figure 5 (and similar spectra for other beams and targets) cannot be used for the calculation of $\delta D_n$. Corrections for losses and shifts in the spectrum due to nuclear interactions that occur in beamline materials other than the target are needed,
Figure 4. Charge histogram of the Fe beam data in figure 3, replotted assuming that $Z$ is proportional to the square root of the pulse height, multiplied by a scaling factor to force the Mn (charge 25) peak to appear with its center at 25.0.

Figure 5. Data from figure 4 rebinned, before corrections (gray bars) and after (black bars). The trigger bias causes the uncorrected probability of detecting a surviving primary to appear well below the probability after corrections, and the converse is true for the unresolved events at the low end of the spectrum, since those events are most likely to produce a trigger in one of the off-axis systems.

and most importantly a large correction must be made to remove the bias introduced by the trigger prescaling. To obtain these correction factors, we select the events corresponding to a particular charge, and make a histogram of the latch value for those events. The number of events with latch value 1 must be increased by the prescale factor used in the particular run being
Table 1. $\delta D_n$ values, multiplied by 100, so that the units are dose reduction in per cent per gram per square centimetre of target depth.

| Beam ion | $E$ (GeV nucleon$^{-1}$) | C target | CH$_2$ target | Al target | Fe target |
|----------|--------------------------|-----------|---------------|-----------|-----------|
| C        | 3                        | 2.50      | 3.37          | 1.72      | 1.31      |
| C        | 5                        | 2.61      | 3.64          | 1.87      | 1.14      |
| C        | 10                       | 2.55      | 3.47          | 1.85      | 1.01      |
| Si       | 3                        | 3.54      | 4.93          | 2.42      | 1.53      |
| Si       | 5                        | 3.66      | 5.63          | 2.54      | 1.66      |
| Si       | 10                       | 4.20      | 5.72          | 2.68      | 1.90      |
| Fe       | 3                        | 4.02      | 6.57          | 2.46      | 1.57      |
| Fe       | 5                        | 4.17      | 6.15          | 2.73      | 1.60      |
| Fe       | 10                       | 4.00      | 5.94          | 2.35      | 1.59      |

analyzed, and the events with latch values 8 and higher are not increased. If the fraction of events with latch value 1 is given by $f$, and the prescale factor by $p$, the corrected number of events with charge $Z$ is given by $N_{\text{corr}}(Z) = N_{\text{meas}}(Z)[1 + f(p - 1)]$. The corrected spectrum is shown with black bars in figure 5. Comparing to the gray bars in the same figure, the effect of removing the trigger bias is quite evident. Whereas the other corrections for losses in the stack are on the order of a few percent, the re-weighting increases the primary fluence by about 20% and reduces the fluence of unresolved events by nearly a factor of two.

4.3. Calculation of average LET

With the fully corrected $\phi$ versus $Z$ spectra available, it is straightforward to calculate the average LET of the particle distributions. First, a careful calculation of the beam LET as it emerges from the target is performed and that value, $L_{\text{beam}}$, is assigned to the primary. Then, for every fragment species with charge $Z$, $L(Z) = L_{\text{beam}} Z^2/Z_{\text{beam}}^2$. The sum of $\phi(Z) L(Z)$ is the average LET, since $\sum \phi(Z) = 1$ by definition. These are translated to dose reduction results and compared to our measurements at lower energies in the next section. This assumes that all particles are at equal velocity, which of course is not precisely true. However, we expect velocity distributions to be quite narrow in these data compared to the data used in the earlier analyses. The dose reduction results are shown in table 1.

The nine data points obtained with polyethylene allow us to extend the energy range of the previous measurements, some of which were shown in figure 1. The $\delta D_n$ results for the high-energy beams have been extrapolated to zero depth (see the following section for details) and are shown in figure 6. Unlike the results at 600, 800 and 1000 MeV nucleon$^{-1}$, the high-energy results show significant dependence on the ion species and modest dependence on energy. The latter is undoubtedly due to two salient facts: firstly, in the energy range measured here, the beams are all at or near the minimum of their $dE/dx$ versus energy curves; secondly, the fragmentation cross sections are weakly dependent on energy. At these beam energies, the energy lost in the target by surviving primaries does little or nothing to shift the LET of those particles relative to their LET at the target entrance. The change in LET of surviving primaries is an important effect at lower energies, and increasingly so as beam energy decreases. For thin or moderately thick targets, where the probability of a primary interaction is on the order of
50% or less (sometimes much less), the surviving primaries strongly influence the average LET of the distribution seen downstream of the target. When the energies are such that the particles are in the $1/\beta^2$ region of the $dE/dx$ curve, the decrease in velocity of primaries in the target increases their LET enough to compensate, or more than compensate, the decrease in average LET brought about by fragmentation. Thus it is possible for the average LET to be increased by the target, resulting in a net increase in dose per particle. (With our definition, such results appear as ‘negative dose reductions’, for lack of a better description.) However, in the high-energy data sets analyzed here, this effect does not exist to any significant degree, and decreases are seen in all cases. As described in [7], the $\delta D_n$ results are driven by a competition between energy loss, which increases average LET’s, and fragmentation, which decreases them. At low beam energy, even in the domain where targets must be kept thin to allow the beam to pass through, the energy loss effects dominate. As the beam energy is increased, fragmentation becomes more important, and at moderate energies, the two effects are nearly in balance. With the right choice of beam ion and energy, this balance can produce a Bragg curve that is flat over the so-called entrance region with a large peak in the stopping region, a combination which is useful in heavy-ion radiotherapy. At higher energies, the Bragg curve falls for many centimetres over the entrance region, because the effect of fragmentation dominates the very small changes due to energy loss in the target.

4.4. Extrapolation to zero target depth

To compare the shielding effectiveness of various materials using a 1 GeV nucleon$^{-1}$ $^{56}\text{Fe}$ beam, data were fit (where possible) to obtain $\delta D(0)$, i.e. $\delta D_n$ at zero target depth. When only one target depth of a particular material was available, a correction factor was applied according to $\delta D(0) = \delta D_n e^{bx}$ where $b$ was determined empirically. We wish to apply a similar correction here, but because only one depth was used per target material, we have no experimental

Figure 6. Dose reduction at zero depth for polyethylene targets. Unlike the lower-energy data shown in figure 1, the high-energy data show a considerable dependence of $\delta D$ on the beam ion.
information about $b$. In the 1 GeV nucleon$^{-1}$ data, $b$ was found to be dependent on the target. We can use our Monte Carlo simulation program to estimate the $b$'s needed to make the corrections to the present data. This program [10], now called ‘BBFRAG’ (for Bethe–Bloch and fragmentation) combines cross sections from NASA’s NUCFRG2 model [11] with precise energy loss calculations to simulate accelerator-based fragmentation experiments. Its main deficiency is that it is a one-dimensional code and follows only one fragment emerging from each nuclear interaction. Thus the high-$\Delta E$ portion of the simulated detector spectrum, which is dominated by surviving primaries and heavy fragments (those with about half the beam charge or more) tends to reproduce the data reasonably well, but the portion at lower $\Delta E$ is not accurately simulated. Not coincidentally, it is the portion of the detected spectrum where fragment charges are well resolved that is fairly well simulated; and, most importantly for the measurement described here, this is the region that most strongly influences the average LET of the entire distribution. The simulation is therefore expected to be reasonably accurate for predicting both $\delta D_n$ and $b$, though we expect that the lack of non-leading fragments in the simulation will lead to overestimates of $\delta D_n$. The effect of this shortcoming on estimated $b$ values is not as easy to predict.

In addition to the lack of multiple fragments in the simulation, an extensive series of measurements has shown that, while NUCFRG2 charge-changing cross sections tend to be accurate to better than 10%, its predicted fragment production cross sections are accurate only at about the $\pm$ 30% level for fragments with $Z$ above $Z_{\text{beam}}/2$. For larger charge changes, the model is even less accurate. Even so, as we will show, the predicted $\delta D_n$ values from the simulations are reasonably close to the measured values, suggesting that, for this purpose, the details of the fragment distributions are not critical.

4.5. Monte Carlo simulations of the experiment

A simulation of each combination of beam ion, energy and target material was run, each with modest statistics. It was not necessary to fully simulate the beamline as configured in the experiment; only the targets were described in the input files. BBFRAG contains an option that populates a histogram of LET for every line in the input file. We used this feature to determine the calculated $\delta D_n$ at 5, 10, 15 and 20 g cm$^{-2}$ target depths, and these results were then fit to determine $\delta D(0)$ and $b$ for each material. As a check of the accuracy of the simulation, figure 7 shows the measured [6] values versus the calculated values for 1 GeV nucleon$^{-1}$ $^{56}$Fe. As expected, the calculated $\delta D(0)$ values are all higher than the measurements, owing to the fact that only one fragment is produced per nuclear interaction in the model. The average ratio of measured to calculated $\delta D(0)$ is 0.90, with a standard deviation of 0.049. The ratio of measured to calculated $b$ averages 1.03, with a standard deviation of 0.14. We therefore estimate that the calculated $b$ values used in the extrapolations to zero depth for the 3, 5 and 10 GeV nucleon$^{-1}$ data are good to $\pm$15%. The propagated uncertainty on any given correction factor is given by $x e^{\delta} \sigma_b$ and must be computed case-by-case. We find the typical relative errors on the $\delta D(0)$ values to be about 1.0–1.5%. The worst cases are for the $^{28}$Si and $^{12}$C beams with the Fe targets, which were thick (15 and 19 g cm$^{-2}$, respectively), and which in two instances (out of 36 total considered here) yield relative errors of 2.5 and 2.7%. Even the largest of these is much smaller than the uncertainties attributable to other sources, as described below. We therefore ignore this source of uncertainty in the following, since any contributions would be added in quadrature with much larger errors and would have a negligible effect.

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Figure 7. Measured versus calculated values of $\delta D(0)$ and $b$ for the 1 GeV nucleon$^{-1}$ $^{56}$Fe data of [6].

4.6. Results at zero depth for all materials

The extrapolated results, i.e. $\delta D_n e^{b_x}$, are shown as three bar charts in figure 8 (one chart per beam ion species, each with a different $\delta D(0)$ scale). As in earlier work, hydrogen produces by far the largest dose reduction of any material, and shielding effectiveness is seen to drop steadily as the target mass number increases. For each beam ion, the differences between the three beam energies are quite small, perhaps negligible in view of the uncertainties (discussed below). Energy independence, or very weak dependence is expected from the considerations discussed above, since the LET of primaries surviving the target is essentially unchanged by the target. If we assume energy independence and compute the standard deviations, we find for all beams and targets the results are in the 2–10% range, comparable to (in many cases smaller than) the uncertainties.

Unlike the data in figure 1 for lower energies, there appears to be dependence of the high-energy $\delta D_n$ results on the beam species, at least for the lower-mass targets. For example, for polyethylene, the $\delta D(0)$ values increase by almost a factor of two in going from the average value of 0.037 (g cm$^{-2}$)$^{-1}$ obtained for the $^{12}$C beams to the 0.068 (g cm$^{-2}$)$^{-1}$ obtained for $^{56}$Fe beams. In contrast, for Al and Fe targets, the differences on a percentage basis are considerably smaller, with $\delta D_n$ being about 1.4 times higher for $^{56}$Fe beams than for $^{12}$C.

Some obvious trends can be seen in figure 8. In all cases, $\delta D(0)$ is a monotonically decreasing function of the target mass number. For any given target material, the largest $\delta D(0)$ values are typically seen for the $^{56}$Fe beams, followed by the $^{28}$Si beams, with the $^{12}$C beams invariably showing the smallest effects. In the $^{56}$Fe chart, the 1 GeV nucleon$^{-1}$ data have been included to provide an additional point of comparison. In the Fe beam data, for the targets
Figure 8. Dose reduction results at zero depth for all three beams, all three energies of each, and all four targets. Note the different abcissas in each of the plots.

other than CH$_2$ (and hence H), the largest dose reductions are found at 5 GeV nucleon$^{-1}$; in the Si beam data, for all targets, the largest reductions are at 10 GeV nucleon$^{-1}$; and in the C beam data, for all targets except Fe, at 5 GeV nucleon$^{-1}$. These do not follow any obvious pattern, and it may be that, in view of the uncertainties (see the following section), the results should be considered energy independent or nearly so. It is clear, though, from the Fe data, that dose reductions at 3, 5 and 10 GeV nucleon$^{-1}$ are larger (as expected) than they are at 1 GeV nucleon$^{-1}$, as expected from basic considerations of the Bragg curve behavior at these energies.

To better gauge the trends in the data, it is instructive to normalize the data for each beam ion/energy combination to the corresponding result for polyethylene, as in figure 9. It is evident from this plot that the effectiveness of the different target materials relative to CH$_2$ decreases as the charge and mass of the beam ion increase. Consider the Al target data shown as triangles in the figure; the carbon beam data have the highest relative effectiveness, followed by the silicon...
beam data, followed by the iron beam data. The same trend holds for C and Fe targets as well, almost without exception. Thus the advantage of CH$_2$ relative to other materials depends on the beam ion, but has little or no dependence on its energy, at least in the range covered here.

4.7. Uncertainty estimates

As described above, the extrapolation to zero depth is a source of systematic uncertainty at the level of about $\pm$2%. Given the complications of the data analysis—the relatively poor detector resolution, the trigger bias and removal, etc—it is difficult to make quantitative estimates of the additional sources of uncertainty. However, in another experiment at the AGS in 2002, we obtained another data set with a 5 GeV nucleon$^{-1}$ $^{56}$Fe beam. That experiment was performed with our typical setup, including an unbiased trigger and good detector resolution. We can directly compare the dose reduction results obtained in that experiment to the 5 GeV nucleon$^{-1}$ $^{56}$Fe results obtained from the 2005 data, and we can use the differences to estimate the systematic errors in all of the results from the 2005 experiment.

In the 2002 experiment, different target depths were used for C and Al, and a Cu target was used instead of Fe. In order to eliminate any differences owing to the variability of the target depths, we have extrapolated the 2002 data to zero depth using the same method and constants as were applied to the 2005 data. The resulting $\delta D(0)$ results show differences of 5–10% for C, CH$_2$ and Al targets. The Cu and Fe results, though not directly comparable, should be similar. We expect that the Cu target should yield a slightly smaller $\delta D(0)$ than the Fe target, but the reverse is found, with the Cu $\delta D(0)$ result being about 10% higher than that for Fe. In all cases, the $\delta D(0)$ values derived from the 2002 data are larger than their counterparts in the 2005 data.

The differences in the two 5 GeV nucleon$^{-1}$ $^{56}$Fe data sets are indicative of the systematic errors in measurements, since they should in principle yield identical results. Based on the observed differences, we conservatively estimate that the results above for C, CH$_2$ and Al targets are accurate to within $\pm$10%, and the Fe results within $\pm$15%. The results for H are given by $\delta D_H(0) = 7\delta D_{CH_2}(0) - 6\delta D_C(0)$. If we simply propagate the 10% uncertainties in the CH$_2$ and C measurements, ignoring the correlations (i.e. the off-diagonal term in the covariance matrix), the uncertainties on $\delta D_H(0)$ would be of the order of 100%. However, the covariance
term is large and negative, and therefore cannot be ignored; it brings the relative error on each H data point down to about ±10% for Fe beams, 15% for Si beams and 5% for C beams. This is based on a standard method for estimating the covariance (for which we must assume energy independence of the results). Making a direct comparison of the H results from the 2002 and 2005 experiments, we find $\delta D(0)$ of 0.201 (g cm$^{-2}$)$^{-1}$ for the 2002 data, only about 1% different from the value of 0.199 (g cm$^{-2}$)$^{-1}$ obtained with the 2005 data.

4.8. Comparison with Monte Carlo GCR results

In [7], we showed Monte Carlo results using a BBFRAG simulation of the GCR (with the input flux based on the Badhwar–O’Neill model [12]). We found that polyethylene reduced the dose due to GCR heavy ions (defined as charge 3 and higher) by about 7% (g cm$^{-2}$)$^{-1}$. We experimentally measured a maximum value of about 5% (g cm$^{-2}$)$^{-1}$ (with 1 GeV nucleon$^{-1}$ beams), and hypothesized that higher-energy beams would yield significantly larger $\delta D$’s, pulling up the average over the GCR energy spectrum, which includes a significant portion above 1 GeV nucleon$^{-1}$. However, we find here that even in largest measured $\delta D$, that for 3 GeV nucleon$^{-1}$ $^{56}$Fe, is only about 7% (g cm$^{-2}$)$^{-1}$, with several other measurements yielding values between 5 and 7% (g cm$^{-2}$)$^{-1}$. Thus the hypothesis is not entirely correct, but we believe it is only slightly in error, because we did not take sufficient account of the fact that the Monte Carlo generally overestimates dose reduction due to its neglect of non-leading fragments. The effect is shown in figure 10, where we plot $\delta D(0)$ as calculated by BBFRAG against the measured values. With very few exceptions, the calculated $\delta D$ values are larger than the measured. Specifically for CH$_2$, 7 of 9 predictions are too large, by an average of 8.7%.

Figure 10. Scatter plot of measured and calculated dose reduction results at zero depth for all beams and targets in the present study.
It therefore appears likely that the true dose reduction by CH$_2$ against GCR heavy ions would be closer to 6% (g cm$^{-2}$)$^{-1}$, and that the measured values of 5–7% for the high-energy Si and Fe beams presented here bracket this result.

5. Conclusions

We have measured the shielding effectiveness of CH$_2$, C, Al and Fe targets placed in $^{12}$C, $^{28}$Si, and $^{56}$Fe beams at 3, 5 and 10 GeV nucleon$^{-1}$, representative of high-energy GCR. In accordance with theoretical predictions and our earlier experimental results, dose reductions per gram per square centimetre of target depth are found to be largest for CH$_2$, owing to its hydrogen content, and decreasing reductions are seen with increasing target mass number. The absolute values of dose reduction are larger at these energies than at lower energy, owing to the dominance of nuclear fragmentation effects over energy loss effects. At lower energies, the two mechanisms play competing roles and dose reductions are strongly dependent on beam energy. Here, energy dependence is weak, perhaps negligible, but significant dependence on the ion species is seen.

The measured results have been compared to the BBFRAG Monte Carlo program. Because the code is one-dimensional and only follows one fragment emerging from each nuclear interaction, it tends to underestimate the energy deposited, or average LET, at the target exit. This leads to systematic overestimates of dose reduction. When GCR fluxes from the Badhwar–O’Neill model are used to simulate the shielding of polyethylene against GCR heavy ions, the code predicts an average dose reduction of about 7% (g cm$^{-2}$)$^{-1}$, which matches the largest dose reductions seen in the data. Since the real average dose reduction in the GCR environment is unlikely to be as large as the largest value measured here, we infer that (not surprisingly) the Monte Carlo estimate is too high, probably by 5–10%. Thus a more realistic expectation is that polyethylene would provide a dose reduction of about 6–6.5% (g cm$^{-2}$)$^{-1}$, and this is more in line with the measurements, particularly for $^{28}$Si and $^{56}$Fe beams.

We note that when measurements are made directly on the beam axis, as they are here, and when the target is thin enough to allow the primary and projectile fragments to exit, these charged particles dominate the doses. However, away from the beam axis, neutrons (which are not reported upon here) can contribute significantly to the dose, particularly behind thick targets. In the data and Monte Carlo simulations presented here, the neutron contributions are not accounted for, but in other contexts they can be quite important.

More energetic ions, not studied here, could conceivably make a significant contribution to dose in heavily shielded environments. We note that the range–energy relation is highly nonlinear at low energy, but above a few GeV/nucleon, becomes approximately linear. Behind thick shielding, for the sake of argument, say 40 g cm$^{-2}$ aluminium equivalent, a 1 GeV nucleon$^{-1}$ $^{56}$Fe ion that does not undergo fragmentation will be stopped, whereas at an energy of 10 GeV nucleon$^{-1}$ or higher, the ion can penetrate the shield. Of course, the most likely outcome of a high-energy Fe ion entering such a thick shield is a fragmentation reaction (or two), but in that instance too the higher energy ions produce a larger dose at the target exit due to the production of a greater number of more energetic secondaries. Thus, even though the flux as a function of energy drops rapidly at high energies, it is possible that in some scenarios ions in the 10–100 GeV nucleon$^{-1}$ energy range may play an important role.

Additional measurements with a less complex experimental set-up and additional beam ions would be helpful, but are unlikely to occur given the closure of the AGS. It will be instructive to compare the results of the tests presented here to results returned by the CRaTER

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instrument [13] aboard the Lunar Reconnaissance Orbiter, to be launched into lunar orbit in 2008. The instrument contains silicon detectors separated by significant depths of tissue-equivalent plastic (similar to polyethylene) and will be exposed to the full GCR environment.

Finally, it is worth noting that these studies point strongly to the importance of using low-Z materials in a spacecraft hull. The reasons are evident in figure 9 above. Relative to polyethylene, which has proven to be the most effective material we have tested, aluminium provides less than half the benefit per unit mass, but carbon provides 70–80% of the benefit. Assuming a shield depth of 5–10 g cm$^{-2}$ would be feasible for an actual deep-space mission, a dose reduction of 30–50% is obtainable if materials research were to yield a structural material with shielding properties equal to polyethylene. Since estimated exposures to the GCR on a hypothetical three-year Mars mission are on the order of 0.5–1 Sv of dose equivalent, close to (and in some cases above) the present career limits for low-earth orbit, a reduction of 30–50% in dose would be significant. On the other hand, using aluminium would reduce the dose from charged particles by about half as much, i.e. 15–25%, and would also yield a higher dose from neutrons than would a material with a lower mass number.

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