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# Measurements of galactic cosmic ray shielding with the CRaTER instrument

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[1] The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument aboard the Lunar Reconnaissance Orbiter has been measuring energetic charged particles from the galactic cosmic rays (GCRs) and solar particle events in lunar orbit since 2009. CRaTER includes three pairs of silicon detectors, separated by pieces of tissue-equivalent plastic that shield two of the three pairs from particles incident at the zenith-facing end of the telescope. Heavy-ion beams studied in previous ground-based work have been shown to be reasonable proxies for the GCRs when their energies are sufficiently high. That work, which included GCR simulations, led to predictions for the amount of dose reduction that would be observed by CRaTER. Those predictions are compared to flight data obtained by CRaTER in 2010–2011.

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## 1. Introduction

[2] The Lunar Reconnaissance Orbiter (LRO) spacecraft was launched to the Moon in July 2009. The instrument payload includes the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) [Spence *et al.*, 2010], which has provided the first detailed measurements of energetic charged particles in lunar orbit. These particles are of interest because of the radiation dose and associated health risks they impart to humans in space. Possible detrimental health effects include cataract and cancer induction [Cucinotta and Durante, 2006], and chronic damage to the central nervous system [Nelson, 2009].

[3] Outside the geomagnetosphere, the principal sources of such energetic charged particles are the galactic cosmic rays (GCRs) and solar particle events (SPEs).

The flux of the GCRs is continuous and varies by factors of 2 to 3 with the solar cycle, while SPEs are sporadic, being possible at any point in the solar cycle but most likely to occur at or near solar maximum. SPEs can produce large dose rates, typically for short periods of time (hours or days), and typically in the form of relatively low-energy protons that can be stopped in moderate depths of shielding. In solar quiet time, GCRs are the dominant source of radiation dose and hence risk. Shielding against GCRs is difficult owing to their high energies. As discussed in the following, the design of CRaTER enables tests of shielding against GCRs.

## 2. The CRaTER Instrument

[4] CRaTER has been described in detail in the literature [Spence *et al.*, 2010]. A schematic drawing of the particle telescope is shown in Figure 1. The end of the telescope with detectors D1 and D2 faces the zenith direction and is shielded only by a thin window (0.76 mm in depth). At the other end, D5 and D6 are similarly shielded by a 30 mil window. When LRO is in its nominal 50 km circular mapping orbit, the field of view defined by the D5 and D6 detectors is entirely filled by the lunar disk; this was the case for all flight data presented here. Albedo neutrons [Mitrofanov *et al.*, 2012] coming from the surface are of considerable interest from both the planetary science and radiation protection perspectives, but are not considered in the analysis presented here. Recent work on

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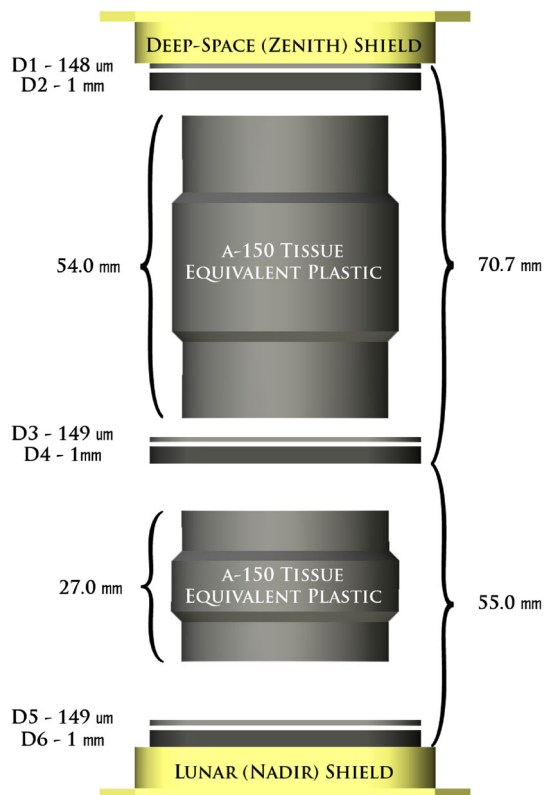
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**Figure 1.** Schematic drawing of the CRaTER telescope, which includes six silicon detectors and two pieces of tissue-equivalent plastic.

albedo protons, which are also of interest dosimetrically, has also been published [Wilson *et al.*, 2012].

[5] CRaTER is unusual compared to other particle detectors that have flown in space in that it combines particle detectors with large pieces of A-150 tissue-equivalent plastic (TEP). Silicon detectors record the energy deposited ( $\Delta E$ ) by charged particles that traverse some or all of their active depth. The energy deposition data can be used to study the shielding properties of the TEP against high-energy GCRs.

[6] The first TEP piece (TEP1) has an areal density of  $6.09 \text{ g cm}^{-2}$ , comparable to the shielding of the blood-forming organs in the human body. This shields the D3-D4 detector pair against GCRs incident from the zenith end of the telescope. A large majority of GCRs that enter CRaTER have energy sufficient to penetrate TEP1, but many of the heavy ions—which contribute significantly to the dose and dose equivalent—undergo nuclear fragmentation in the TEP. The secondary ions that emerge from the TEP typically deposit less dose than the incident particle would have, had it not interacted. Thus TEP1 shields the D3-D4 pair against GCR via the fragmentation process. Similarly, the D5-D6 detector pair is shielded against GCR by TEP2 ( $3.05 \text{ g cm}^{-2}$ ), in addition to TEP1.

[7] Few particles produced in typical SPEs have sufficient energy to penetrate TEP1, and even fewer penetrate TEP2. This is more akin to what is thought of as shielding in ground-based facilities: that is, an area is shielded by mass sufficient to entirely stop the primary radiation from reaching it. This is relatively simple from the calculational or modeling perspective, in that it only requires knowledge of the range-energy relationship. The focus of this study is strictly on GCRs incident from the zenith direction, and the shielding effect provided by TEP through nuclear fragmentation. The existing experimental literature on nuclear fragmentation has many gaps [Norbury *et al.*, 2012], and current fragmentation cross-section models have limited accuracy [Silver *et al.*, 2008]. (Models of Galactic Cosmic Rays are also uncertain at the 20%–30% level, but we do not make explicit tests of such models here.) In view of the uncertainties associated with fragmentation, it is of interest to test whether the effects of fragmentation of GCR heavy ions are accurately predicted by existing models, and whether a hypothesis (explained below) developed in ground-based research can be applied to CRaTER data.

## 2.1. Detector Geometry and Sensitivity

[8] The arrangement of detectors and the differences in sensitivity between thin (odd-numbered, with depths of  $148 \mu\text{m}$ ) and thick (even-numbered, depths of  $1 \text{ mm}$ ) silicon detectors leads to some complexity in the interpretation of data. Data from each detector of a pair must be combined to cover the full dynamic range, with the thick detector covering the low-LET range (from  $0.2$  to  $80 \text{ keV}/\mu\text{m}$  in silicon) and the thin detector covering the high-LET range (from about  $10$  to  $2000 \text{ keV}/\mu\text{m}$  in silicon). Note that the units  $\text{keV}/\mu\text{m}$  and  $\text{MeV}/\text{mm}$  are equivalent, and we use them interchangeably here.

[9] Different possible detector coincidences have different geometry factors, which are directly proportional to the count rates. The events used here are D2-D4 and D2-D4-D6 coincidences. The geometry factor  $G$  of the telescope formed by D2 and D4 is  $1.91 \text{ cm}^2 \text{ sr}$ , and the D2-D4-D6 telescope has a  $G$  of  $0.62 \text{ cm}^2 \text{ sr}$ . Thus, the D2-D4 coincidence rate is expected to be about three times higher than the D2-D4-D6 coincidence rate. (The ratio is slightly enhanced by the small fraction of GCRs that stop in TEP2.)

[10] High energy particles with trajectories in the D2-D4 FOV but outside the D2-D4-D6 FOV may nonetheless produce a particle that causes a hit above threshold in D6. Similarly, a trajectory outside the D2-D4 FOV may have a hit above threshold in D4. Although they are due to real particles and not to any sort of detector artifact, these 2- and 3-fold coincidences are not accounted for in the usual geometric factor calculation because the initial trajectory of the incident particle passed outside D4 and/or D6. These events complicate the shielding analysis because their energy deposition patterns may in some cases be indistinguishable from those of valid events in the

FOV. The effect has been successfully reproduced in the laboratory, as explained in Appendix A.

[11] The particles that cause these “out-of-cone” coincidences may be knock-on electrons ( $\delta$ -rays) produced in either silicon or TEP, or projectile fragments produced at a relatively large angle by a nuclear interaction in TEP, or even target fragments. For example, consider an event in which a heavy ion is detected in the first two detector pairs, and the third pair records a particle with charge 1. There are several possible explanations for such an event. The incident ion’s trajectory may have been inside the D2-D4-D6 FOV, but the ion underwent a nuclear interaction in TEP2 that produced only a single fragment in the last detector pair. Alternatively, the incident ion’s trajectory may have been in the D2-D4 FOV but outside the D2-D4-D6 FOV, and the particle seen in the last detector pair was a  $\delta$ -ray, projectile fragment from a nuclear interaction in TEP2, or target fragment from an interaction in TEP2. There are no distinguishing characteristics in the event itself that allow one to determine which of these possibilities caused the observed event.

[12] In the analysis, we attempt to mitigate the effect of out-of-cone events with carefully chosen event selection cuts, but—as we will show—this class of events cannot be eliminated directly. They appear to account for roughly half the events in the final sample. Out-of-cone events can only be removed on a statistical basis, which can take on various degrees of sophistication. The results below make use of a “brute force” approach, which can be refined in the future.

### 3. Fragmentation, Energy Loss, and Dose Reduction

[13] For ion velocity  $v$ , the dose per incident particle is approximately proportional to  $Z^2/v^2$ , where  $Z$  is the ion’s charge. When fragmentation occurs, projectile fragments tend to be forward-going and to approximately maintain the velocity of the incident ion. Given nearly constant  $v$ , the sum of the  $Z^2/v^2$  terms from projectile fragments is always less than the  $Z^2/v^2$  of the original ion. In the context of the CRaTER experiment, ionization energy loss in TEP has the effect of causing the dose per particle to increase after traversing TEP (assuming no fragmentation) due to the ion’s lower velocity at the exit of the TEP. For high-energy particles, the change in  $v$  is negligible, but at some energies, it can be significant. The net effect of the TEP (or any other shielding material), therefore, depends on the charge and energy distributions of the incident ions [Zeitlin, 2012]. Since most GCRs are relativistic, fragmentation is the dominant effect, but the partially compensating effect of energy loss is present as well.

[14] The effectiveness of TEP as a shield against GCR heavy ions can be related to earlier ground-based research performed using heavy-ion beams to study the shielding properties of various materials [Zeitlin *et al.*, 2006; Guetersloh *et al.*, 2006; Zeitlin *et al.*, 2008; Lobascio *et al.*, 2008]. Target materials tested included polyethylene ( $\text{CH}_2$ ),

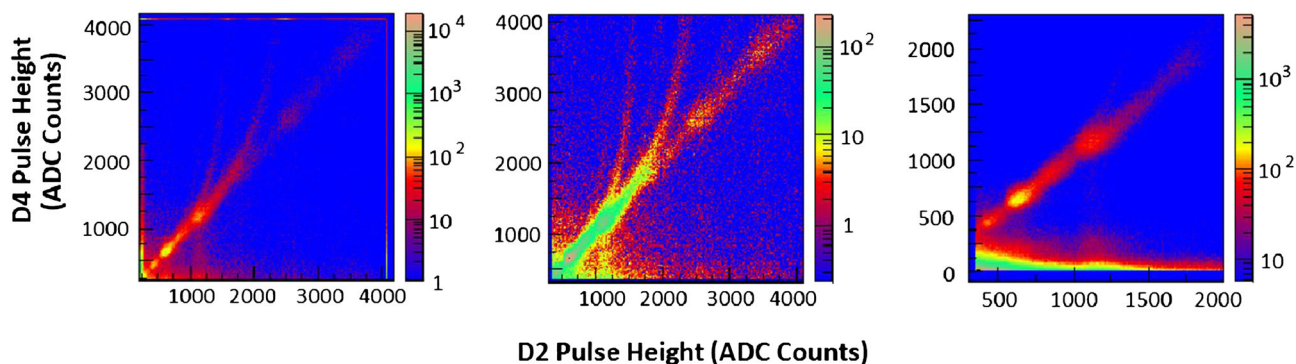
which is chemically similar to TEP. Monte Carlo simulations of GCR shielding were also performed as part of the earlier studies [Guetersloh *et al.*, 2006], and results from CRaTER should (after appropriate selection and normalization) be comparable to those calculations. Weight fractions of carbon are similar between  $\text{CH}_2$  and TEP (85.7% and 77.6% respectively). TEP contains small amounts of N (3.5% by weight), O (5.2%), F (1.7%), and Ca (1.8%) that are not present in polyethylene. Together these make up about 12% of TEP by weight. Further, the weight fraction of hydrogen in TEP is 10.1% compared to about 14.3% in  $\text{CH}_2$ . Since hydrogen produces more fragmentation per unit mass than any other element [Wilson *et al.*, 1995; Zeitlin *et al.*, 2006], we expect somewhat less fragmentation in TEP than in the same areal density of  $\text{CH}_2$ . TEP should therefore be a slightly less effective shield against GCR heavy ions than polyethylene.

[15] Performance of  $\text{CH}_2$  as a shield was systematically studied with a variety of beam ions and energies [Guetersloh *et al.*, 2006]. An important conclusion of the work was that, for a given target, shielding effectiveness was found to be independent of the beam, provided the ion species was 0 or heavier and that the beam energy was at least 600 MeV/nuc. According to predictions of the Badhwar-O’Neill GCR model [O’Neill, 2010] for 2010–2011, about 55% of the heavy-ion flux is at energies above 600 MeV/nuc. Thus, by identifying a sample of high-energy GCRs in CRaTER data, we can relate CRaTER flight data to the ground-based studies, bearing in mind the differences between  $\text{CH}_2$  and TEP.

### 4. General Features of CRaTER Data

[16] The LRO spacecraft was in a varying elliptical orbit for its first few months at the Moon. On 15 September 2009, the spacecraft was placed into a circular, polar orbit with an altitude of 50 km. The present analysis uses data taken from January 2010 through the end of 2011. We have excluded days on which there were significant numbers of solar energetic particles present, and also days on which pulser calibration and/or discriminator sweeps were performed. This leaves about 670 days of data.

[17] Readout of all CRaTER detectors is triggered by any energy deposition greater than the threshold in any single detector. Thresholds in the thick detectors are set to approximately 100 keV, well below the 330 keV of energy that is (on average) deposited by a minimum-ionizing charge 1 particle. Essentially no filtering is performed at the hardware level in CRaTER. The resulting data set is large and must be carefully filtered in ground processing to find the events of interest. The first filter applied here requires that any two of the three thick detectors had hits above threshold. (Events with a particle only seen in D4 and D6 are removed in later filtering.) In addition, a “heavy-ion” filter is applied here that requires at least 4.5 MeV of deposited energy in D2. This energy deposition corresponds to energy depositions from beryllium (charge 4) and heavier ions,



**Figure 2.** Scatter plots of energy deposited in D4 versus D2 for a subset of the heavy-ion data sample (left panel) with pulse heights above 200 ADC counts in both detectors, (middle panel) for pulse heights above 350 ADC counts in both, and (right panel) with no restrictions on the D4 pulse height.

at typical GCR energies. Low-energy helium ions can (and do) satisfy this cut, but these events can easily be identified and removed from the sample. (This is because such events invariably have large energy deposits in D4 compared to D2, due to energy lost traversing TEP1.) The effect of the two filters is a reduction of the data volume by three orders of magnitude.

#### 4.1. Correlations Between Detectors

[18] Figure 2 shows three scatter plots for a sample of events that pass the two-stage filter defined above. The different panels emphasize different areas of the overall plot. In all panels, the pulse height in D4 is plotted on the  $y$  axis and that in D2 on the  $x$  axis. In Figure 2(left), the data sample has been restricted to events with pulse heights above 200 ADC counts (about 4.4 MeV) in both detectors. In Figure 2(middle), the minimum value is 350 ADC counts (about 7.7 MeV) in both detectors, and the color scale is adjusted accordingly, bringing several features into visibility. In Figure 2(right), no cut is made on the minimum D4 pulse height, while D2 was required to have a pulse height above 350 ADC counts.

[19] 1. Bands are seen along the  $45^\circ$  line in all plots, populated by events in which the same ion was measured in D2 and D4, and its velocity had not changed significantly in traversing TEP1. Bright spots can be seen along this line for boron ( $Z = 5$ , centered near 450 ADC counts in both detectors), C (650 ADC counts), and O (1200 ADC counts). Fainter clusters can be seen for Mg ( $Z = 12$ ,  $\approx 2600$  ADC counts) and Si ( $Z = 14$ ,  $\approx 3500$  ADC counts). Each bright spot or cluster is due to highly relativistic ions of a particular species, because as velocity  $v$  approaches  $c$ ,  $\Delta E/\Delta x$  tends towards a single value for a given  $Z$ .

[20] 2. A nearly vertical band is seen in the lower left-hand corner of Figure 2(left), roughly parallel to the  $y$  axis with D2 pulse height of about 250 ADC counts. This band is populated by helium ions that lose significant energy in TEP1 and therefore deposit much more energy in D4 than in D2.

[21] 3. Events in which one or both readouts saturated are seen in Figure 2(left), creating lines at pulse height values of 4095, running parallel to either axis.

[22] 4. In Figure 2(middle), several bands above the  $45^\circ$  line are seen, with the D4 pulse height increasing rapidly compared to the D2 pulse height. The most heavily populated of these are due to C ( $x \approx 1400$ ) and O ( $x \approx 2000$ ). Fainter bands due to boron, nitrogen, and neon ions are also visible. The ions populating these bands lost significant energy in TEP1.

[23] 5. Figure 2(right) is dominated by a band of events with small, but in many cases non-zero, pulse heights in D4. This region of the plot includes particles that miss D4, and also those events in the “out-of-cone coincidence” category described above (thought to predominantly be caused by  $\delta$ -rays).

[24] Each of these distinctive categories of events plays a role in the shielding analysis described below.

#### 4.2. Modified Calibration

[25] For all detectors, peaks in the pulse height distributions can be associated with elemental peaks corresponding to the highest-energy ions, as will be demonstrated in more detail below. These peaks correspond to the clusters of events seen in the scatter plot described above. A clean sample of high-energy ions can be obtained from the data set plotted in Figure 2 by requiring mutually consistent (to within 10%) pulse heights in D1, D3, and D5, and separately in D2, D4, and D6. In the thin detectors, peaks can be identified corresponding to C, O, Mg, Si, and Fe. In the thick detectors, peaks are seen for He, B, C, O, Ne, and Mg. (To get the He peaks, a separate data set was created with its own filter.) Linear fits were performed to determine offsets and gains. The gains (ADC counts per MeV deposited) found by this method are 5–10% higher than the previously-published values, for reasons explained below. The differences between the two calibration methods were not expected, and are still under investigation. However, the present analysis depends on ratios of deposited

energy, so any scale errors introduced by the new method tend to cancel.

[26] There are several subtle points associated with calibration of thin silicon detectors [Bichsel, 1988]. The nominal gains and offsets given in [Spence *et al.*, 2010] were obtained using low-energy protons. However, the GCRs measured in flight are much more energetic, and straggling, which is negligible at low energy, plays an important role. Straggling in this context means large energy depositions from individual collisions with large energy transfer to individual electrons; these interactions are responsible for the well-known Landau distribution. At high energies, the most probable energy deposit  $\Delta_p$  is always less than the mean, whereas at low energies, the two are more nearly equal. For high-energy particles in a detector of thickness  $t$ ,  $\Delta_p/t \approx a + b \ln t$ , where  $a$  and  $b$  are constants. The logarithmic term arises from the increasing probability of collisions with large energy transfers to single electrons as detector thickness increases.

[27] Bichsel provides a table of calculated  $\Delta_p/t$  for detector depths from 10 to 2560  $\mu\text{m}$  that are well fit by the logarithmic form; from the fit, the ratio of  $\Delta_p/t$  for depths of 1000 and 148  $\mu\text{m}$  is 1.17. Put another way, if there were no straggling, the ratio of energy deposits by a highly relativistic particle in a thin and thick detector pair would simply be the ratio of the depths, i.e.,  $1000/148 = 6.76$ . However, straggling introduces an extra factor, which yields a ratio of thick to thin energy deposits of 7.91 at the highest energies. This effect can be observed in CRaTER data when the nominal calibration factors are used. For a sample of heavy-ion events with well-correlated energy deposits through the stack, the ratio of  $\Delta E$  in D2 to D1 is 7.36, about halfway between the two extremes (no straggling or maximum straggling).

[28] If the GCR consisted only of highly relativistic ions, the correspondence between elemental peaks and  $\Delta_p$  values would be unambiguous. However, the median GCR heavy ion energy is about 1 GeV/nuc, meaning that about half the heavy ions are at lower energies and hence lose comparatively more energy in the detectors. These slower ions do not contribute to the main peaks, but rather tend to broaden them and shift them to higher  $\Delta E$ . A Monte Carlo simulation of GCRs using the BBFRAG code [Zeitlin *et al.*, 1996; Guetersloh *et al.*, 2006] traversing the CRaTER stack was used to estimate the peak locations. BBFRAG simulates nuclear fragmentation using NUCFRG2 cross sections [Wilson *et al.*, 1994] and ionization energy loss. The model of ionization energy loss has recently been modified to use restricted energy loss rather than mean values based on the Bethe-Bloch equation. The restricted energy loss is implemented per the recipe given by the Particle Data Group [Particle Data Group, 2012]. In calculating restricted energy loss, one applies a cutoff energy at the upper limit of the integration over the ionization electron energy distribution. (In contrast, unrestricted energy loss is calculated by setting the cutoff energy to the maximum value allowed by kinematics.) In BBFRAG, this cutoff energy is chosen to correspond to that of an electron with

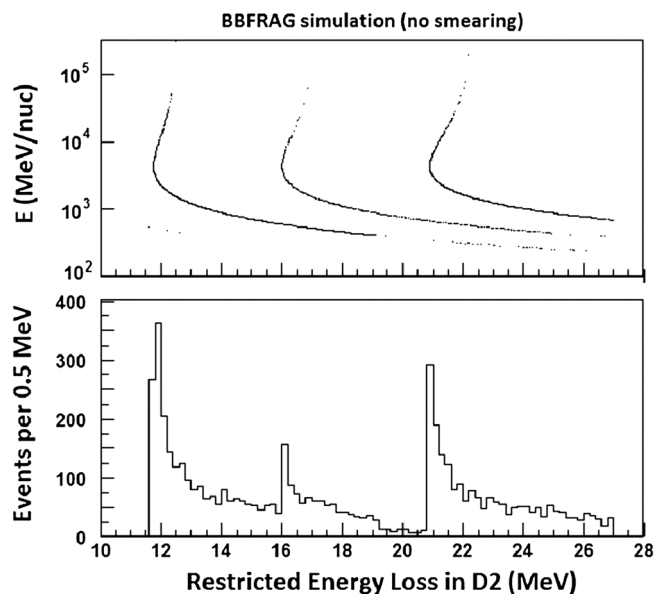


Figure 3. Simulated energy deposition in D2 for C-N-O ions with a GCR-like distribution of kinetic energy. (top panel) In the scatter plot, the restricted energy loss in D2 is plotted against the energy of the simulated particle. (bottom panel) The plot is a histogram of the data in Figure 3(top panel).

a CSDA range of half the detector depth, following the method suggested by [Christie *et al.*, 1987].

[29] Figure 3 illustrates the result of the BBFRAG calculation for a sample of simulated carbon, nitrogen, and oxygen ions with a GCR-like energy distribution. There is no simulation of straggling or the statistical nature of energy deposition. That is, the plotted quantity is in all cases the restricted energy loss for a given ion at a given energy. (Options in the code for generating either Landau or normal distributions were turned off for the simulated data used to make this figure and to estimate the calibration scale.) It can be seen in the histogram at the bottom of the figure that the peaks in the spectrum are due to particles with energies above 1 GeV/nuc.

[30] There is conceivably an overall scale error induced by using restricted energy loss instead of a full calculation of straggling. Two considerations mitigate this concern. First, the simulated ratio of energy deposits in D2 to D1 for high-energy ions is found to be 7.18, close to the value of 7.36 found in the data. Second, the shielding analysis uses ratios of average energy deposits in the different detector pairs, so any systematic scale errors divide out. Thus, for this analysis, it is sufficient that the calibration is done in a consistent manner for all detectors. Additional details are discussed in the following section.

#### 4.3. Combining Thin and Thick Detector Spectra

[31] Analysis of the full spectrum of GCR heavy ions requires use of both the thin and thick detectors in each

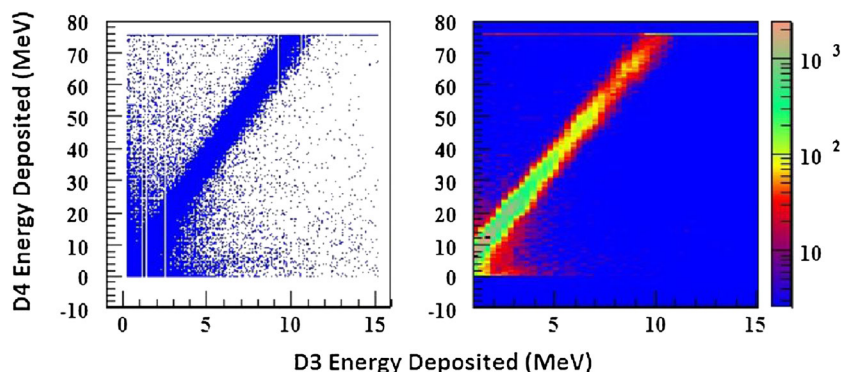


Figure 4. Scatter plots of  $\Delta E$  in D4 versus D3.

pair in order to cover the full range of LET. Figure 4 shows two versions of the scatter plot of energy deposited in D4 versus D3 covering the range where the responses overlap in LET. The event sample shown in Figure 4 was selected by the two-stage filter described above. The revised calibration factors discussed in the preceding section were used in making this plot. The plot contains several notable features. The left plot shows the full scale of D3 energy deposits in this range, whereas the plot on the right is cut off below 1 MeV in D3 to make the color scale more informative. (The color scale applies only to the right plot.) About 95% of the events have well-correlated  $\Delta E$ 's in the two detectors, but the exceptions merit discussion. In particular, the triangular region above and to the left of the band of well-correlated hits, bounded at the top by events with full scale (saturating) hits in D4, is potentially problematic for the analysis. These events are likely due to particles hitting near the edge of the thin detector of the pair, where collection of the ionization electrons is less than 100% efficient [Mazur *et al.*, 2012]. Such events may also be caused by nuclear interactions of ions in D4, i.e., ions that penetrate D3 and deposit a nominal amount of energy, but undergo a collision with a silicon nucleus in D4, leading to large  $\Delta E$  there due to target fragmentation and/or nuclear recoils. Regardless of the cause of the mismatched energy depositions, the ions in this region of the scatter plot are by definition not well-measured, and are excluded from further analysis by means of a graphical cut. Analogous cuts are made in the D2 versus D1 and D6 versus D5 scatter plots. In each case, about 2.5% of the total number of events are removed by the cut. These cuts are referred to as the “triangle” cuts.

[32] It is necessary to make a transition from thick to thin when the thick detector pulse height approaches full scale. To do so, we put the two measurements in terms of  $dE/dx$ , despite the differences between thin and thick detectors when it comes to straggling. In order to make the combined spectrum smooth, we define three regions: (1) Thick detector pulse height less than 3500 ADC counts; (2) thick detector pulse height from 3500 to 4094 ADC counts; (3) thick detector pulse height of 4095 ADC counts (the maximum possible value). In region (1), only the thick

detector is used to determine  $dE/dx$ . Since the thick detectors are 1 mm thick,  $dE/dx$  in MeV/mm is numerically equal to the energy deposition  $\Delta E$  in MeV. (There is also, in principle, a correction for the fact that average paths through the detectors are longer than paths of normally incident particles; however, for D2-D4-D6 coincidences, this is a 1% effect, smaller than the uncertainties in calibration, so this factor is neglected here.) In region (3), only the thin detector is used. In region (2),  $\Delta E$ 's are computed for both, and the thin detector value is multiplied by a factor (obtained from the data) that accounts for its depth and the increased straggling in the thinner detector. The two  $dE/dx$  values are then averaged. For the first detector pair, we refer to the value arrived at in this way as  $\Delta E_{12}$ , for the second pair,  $\Delta E_{34}$ , and for the final pair,  $\Delta E_{56}$ .

[33] The shielding analysis presented below is intended to apply to the mix of GCR ions with charge 8 and above, at energies of about 600 MeV/nuc and higher. These charge and energy ranges allow us to define the desired sample in terms of  $\Delta E_{12}$ . Both energy loss calculations and the data were used to set this range at 17.5 to 270 MeV/mm.

[34] At this stage, final small adjustments were made to the pairwise calibration scales. An event sample was selected in the aforementioned range of  $\Delta E_{12}$  with the additional requirements that  $0.85 < \Delta E_{ij}/\Delta E_{12} < 1.15$  for both  $ij = 34$  and  $ij = 56$ . The GCR simulation suggests that for such a sample, the average energy deposit should increase by about 1.5% in going from the D1/D2 pair to D3/D4, and by another 1% in going to D5/D6, owing to the slight slowing of the ions as they traverse the stack. The overall scales of the two downstream pairs were modified to make the data reflect this, which required upward adjustments of about 3% for both the D3/D4 and D5/D6 pairs. This gives an indication of the relative precision of the calibration method.

## 5. TEP Shielding Analysis

### 5.1. Methods

[35] As noted above, comparisons of spectra in the different detector pairs in CRaTER are complicated by out-of-cone coincidence events in which energy is deposited



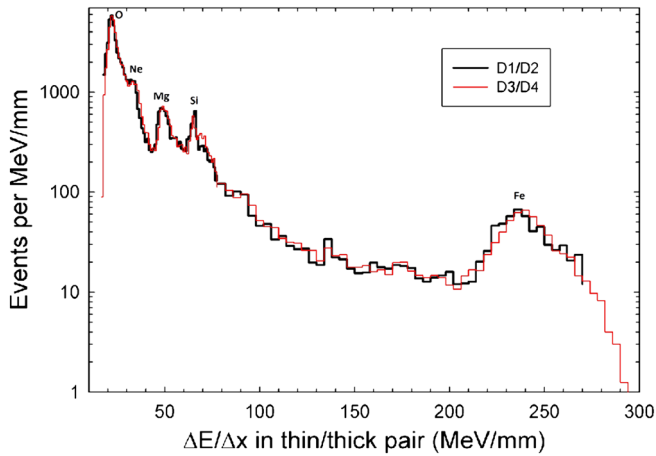


Figure 5. Histograms of  $\Delta E$  per mm in the D1/D2 pair (black line) and in the D3/D4 pair (red line).

in a downstream detector even though the incident particle's trajectory was outside the field of view. An additional consideration is the mix of energies in the data sample: the shielding analysis explicitly pertains to ion energies above about 600 MeV/nuc to facilitate comparisons with ground-based results. For these reasons, we have adopted the following selection cuts for the shielding analysis.

[36] 1. "Triangle" cuts as described above (eliminates events with poor correlation between thin and thick detectors in a pair).

[37] 2.  $17.5 \text{ MeV} < \Delta E_{12} < 270 \text{ MeV}$  to select energetic ions with  $Z$  from 8 to 26.

[38] 3.  $0.95 < (\Delta E_{34} / \Delta E_{12}) < 1.05$

[39] 4.  $\Delta E_{56} > \Delta E_{56}^{\min}$

The cut on the highest value of  $\Delta E_{12}$  removes relatively low-energy iron ions, which are otherwise allowed by the cuts. This cut imposes a minimum energy cut of about 750 MeV/nuc on Fe. At the other end of the charge range, cut 3 effectively imposes a minimum energy requirement of about 600 MeV/nuc on  $^{16}\text{O}$  ions.

[40] With this event selection, the shielding effectiveness of TEP2 can be related to the average  $\Delta E$  in the D5/D6 pair. In this context, TEP1 can be considered to provide an energy filter, since slower particles lose considerable energy traversing it and are therefore rejected by cut 3 above. Figure 5 shows the spectra obtained in the D1/D2 and D3/D4 detector pairs with these cuts. The selection cuts clearly have the desired effect in that the spectrum in the second detector pair is nearly identical to that in the first pair. There are 65,883 events in the sample.

[41] Sharp peaks are clearly visible in Figure 5 for O, Mg ( $Z = 12$ ), and Si ( $Z = 14$ ). Neon ions ( $Z = 10$ ) are visible as a shoulder on the high-end tail for the O peak. The broad peak centered near 230 MeV/mm in both detector pairs is due to Fe ( $Z = 26$ ). The Si peak occurs just below the energy deposition at which the readout electronics

for the thick detectors saturate; this marks the transition where the thin detectors begin to be used. At  $\Delta E$  values above this the data have been averaged over bins that are 4 MeV wide, whereas at lower values the bins are 1 MeV wide. An alternate way of handling the binning is given by [Case *et al.*, 2013].

[42] Given that the D2-D4-D6 geometry factor is about one-third as large as that for D2-D4, we expect that two-thirds of the events selected by cuts 1 through 3 will be due to particles that do not hit D5/D6. We will return to this point below.

## 5.2. Expected Dose Reduction

[43] In related ground-based research [Zeitlin *et al.*, 2006], we defined the quantity  $\delta D_n$  to stand for the change in average dose ( $D$ ) per particle, normalized to the depth of the target in units of  $\text{g cm}^{-2}$ . This proved to be a useful metric for distinguishing between the shielding effectiveness of different materials placed in energetic heavy-ion beams. It can be shown that the change in dose per particle is given by  $(1 - \Delta E_{\text{after}}^{\text{avg}} / \Delta E_{\text{before}}^{\text{avg}})$  where the subscripts refer to measurements on either side of a target in detectors of a given thickness. Here, we consider TEP2 to be the target, the "before" measurement to be the average of the measurements in the D1/D2 and D3/D4 pairs, and "after" to be the measurement in the D5/D6 pair. To get the dose reduction per unit areal density of TEP, we simply divide this quantity by 3.05, the depth of TEP2 in  $\text{g cm}^{-2}$ . The method implicitly assumes that the numbers of events measured before and after the target are equal. This is a trivial point in accelerator experiments with small, highly parallel beams, but not when flight data are analyzed.

[44] In the earlier work, it was explained that, for targets of finite depths, the dose reduction can be expressed as the  $\delta D_n(x) = \delta D_0 \times e^{-bx}$  where  $x$  is the target depth and  $b$  is an empirically determined parameter that varies by material type. Using  $\delta D_0$  allows comparison of materials regardless of the target depth or depths used in the measurement.

[45] A fit to the accelerator data for different materials is given in [Zeitlin *et al.*, 2006]; it allows one to compute  $\delta D_0$  for arbitrary target mass numbers. Using the formula and summing the constituents by their weight fractions in the materials we find values of 0.052 and  $0.047 \text{ g cm}^{-2})^{-1}$  for  $\text{CH}_2$  and TEP, respectively. (The measured value for  $\text{CH}_2$  was 0.051 in the same units.) Thus TEP is predicted to be about 10% less effective than  $\text{CH}_2$  per unit areal density. For polyethylene, we found  $b = 0.0289$ , and a value of 0.0291 for lucite, which is 8.1% hydrogen by weight. TEP is in between the two in terms of its hydrogen weight percentage, suggesting that we can reasonably use  $b = 0.029$ . Overall, then, the predicted dose reduction for TEP2 is  $\delta D_n = 0.047 \times 3.05 \times e^{-3.05 \times 0.029} = 0.13$ . A nearly identical prediction of a 13% dose reduction is obtained using BBFRAG to simulate TEP2 alone in monoenergetic 1 GeV/nuc beams of O, Si, and Fe ions.

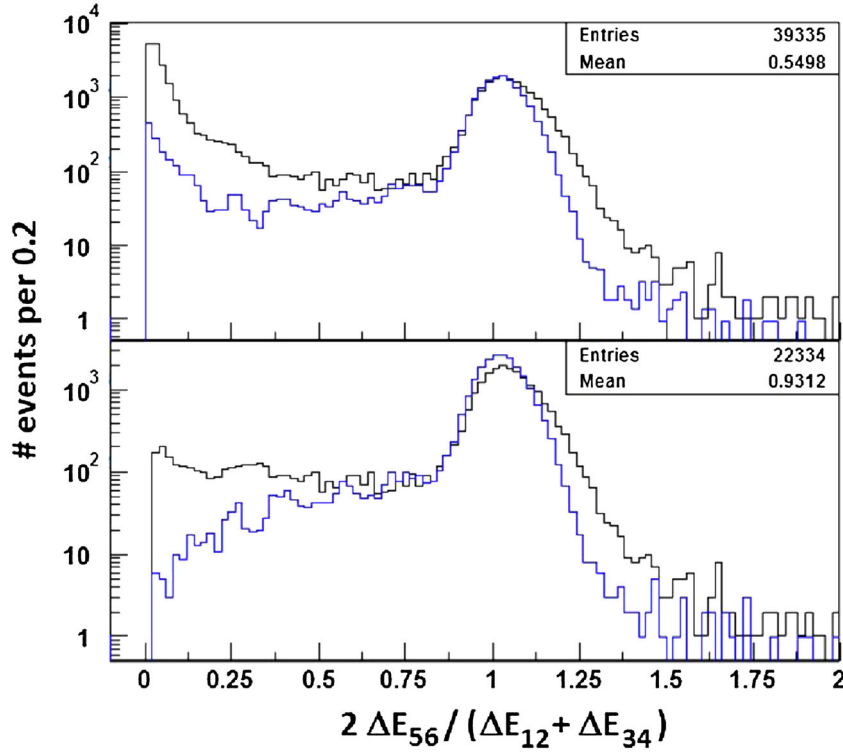


Figure 6. Histograms of the quantity  $f$  as defined in the text, (top panel) for the case of a 0.3 MeV cut on  $\Delta E_{56}$  and (bottom panel) for a 6 MeV cut. In both histograms, data are represented by black lines, and simulation results in blue.

### 5.3. Results

#### 5.3.1. Average Dose Reduction

[46] The event sample defined by cuts 1 through 3 above places no restriction on  $\Delta E_{56}$ . Cut 4, not yet defined, provides for this consideration. Recall that we expect from geometry that only 32.7% of the 65,883 events in the sample will contain valid hits in the D5/D6 pair.

[47] The minimum mean energy deposited by a  $Z = 1$  particle in a 1 mm thick detector such as D6 is about 0.33 MeV. If we set the value of cut 4 to 0.3 MeV, 59.7% of events survive, nearly double the expected fraction. This is undoubtedly caused by the out-of-cone coincidences described above. In addition to the implausibly large fraction of events passing cut 4 when it is set to 0.3 MeV, we find an even less plausible value of  $\delta D_0 = 0.17 \text{ (g cm}^{-2}\text{)}^{-1}$ , about four times larger than expected.

[48] The shielding effectiveness  $\delta D_n$  depends on  $[1 - 2\Delta E_{56}^{\text{avg}} / (\Delta E_{12}^{\text{avg}} + \Delta E_{34}^{\text{avg}})] \equiv 1 - f$ . It is instructive to look at  $f$  as defined here on an event-by-event basis. It is also necessary to make a cut on the maximum allowable value of  $f$ , as large values (say  $> 2$ ) indicate either a slow ion that somehow passed the other cuts, or underwent a nuclear interaction in D6, rendering that value of  $\Delta E$  unreliable since here we are only interested in fragmentation occurring in TEP2. Figure 6(top panel) shows  $f$  as a histogram with a cut of 0.3 MeV on the energy deposited in the

D5/D6 pair (i.e., a  $\Delta E$  significantly greater than 0) and a maximum value of 2.0 for  $f$ . Also shown (in blue) is a histogram from the BBFRAG simulation described in section 4.2 with identical cuts. Recall that the simulation lacks a model of  $\delta$ -ray production. Both real and simulated data have peaks just above a ratio of 1.0, well-populated tails on the low side, and sparsely populated tails on the high side. (Note that the number of events in the simulated data set has been adjusted so that the peak bin contains the same numbers of events as in the real data.) The simulation results shown in this figure have had an ad hoc Gaussian smearing applied, but with the width chosen, this does not produce as broad a peak as is seen in the data. (The Gaussian smearing is meant to crudely represent the combined effects of straggling, electronic noise, and any variations in thickness across the faces of the detectors.) The main differences are seen for  $f < 0.75$ , especially at the lowest values of  $f$ . There are many events in the data with small energy deposits in D5/D6 that are indistinguishable from events in which the primary GCR ion fragmented in TEP2 and produced a small number of light fragments that hit D5/D6. Figure 6(bottom panel) shows a similar plot, but with a cut of 6 MeV for the minimum value of  $\Delta E_{56}$ . With this cut, the shape of the data histogram below  $f = 0.75$  resembles that obtained from the simulation with a cut of  $\Delta E_{56} > 0.3 \text{ MeV}$  as

**Table 1.** Shielding Analysis Results as a Function of  $\Delta E_{56}^{\min}$ 

$\Delta E_{56}^{\min}$ (MeV)	$\Delta E_{\text{before}}^{\text{avg}}$ (MeV)	$\Delta E_{56}^{\text{avg}}$ (MeV)	Fraction Surviving $\Delta E_{56}^{\min}$ cut	$\delta D_n$ ( $\text{g cm}^{-2}$ ) <sup>-1</sup>
0.3	50.4	24.5	0.597	0.169
1	52.4	30.3	0.480	0.138
2	52.8	35.2	0.410	0.109
3	52.3	37.8	0.380	0.091
4	51.6	39.5	0.362	0.077
5	51.0	40.8	0.349	0.066
6	50.6	41.9	0.339	0.057
7	50.3	42.7	0.331	0.049
8	50.0	43.3	0.326	0.044
9	49.5	43.8	0.321	0.038
10	49.3	44.3	0.317	0.033

in Figure 6(top panel). However, in the simulation, the 6 MeV cut has severe consequences for  $f < 0.5$  and the large discrepancy between the data and the simulation for a given cut value persists.

[49] In each histogram in Figure 6, the number of events in the data and the mean value of  $f$  in the data are shown in the upper right corner. These means are not the same as the means that are used to calculate  $\delta D_n$ , but they are informative nonetheless. In Figure 6(top panel), the mean is about 0.55, whereas in Figure 6(bottom panel), it is 0.93. The result is therefore extremely sensitive to the cut on minimum energy deposited in D5/D6. The analysis was repeated with many values of this cut; results are shown in Table 1. In the fourth column of the table is the fraction of events that pass the cut on D5/D6 energy. Since the out-of-cone events are indistinguishable from valid events, the number of events surviving the cut is inflated. At this point, we take guidance from the geometry factor ratio, which dictates that 32.7% of events selected based on comparing D1/D2 and D3/D4 will have valid hits in D5/D6. We can accordingly constrain the results for  $\delta D_n$  by considering only the cut values that produce a surviving fraction of events reasonably close to 0.327. As can be seen in Table 1, cut values between 6 and 9 MeV meet this criterion.

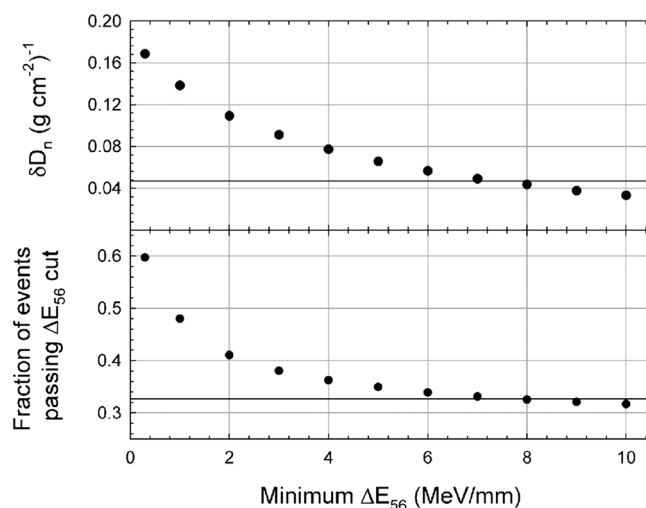
[50] The results in Table 1 are plotted in three different ways in Figures 7 and 8. Both panels of Figure 7 show measured quantities as functions of the  $\Delta E_{56}$  cut value; in the upper panel, we show  $\delta D_n$ , in the lower, the fraction of events that pass the cut. For both, the expected values are shown as lines, and for both, the data approach the lines from above and cross at cut values of 7–8 MeV. This is a remarkably large value of the cut; for relativistic particles, such a large energy deposition corresponds to boron ( $Z = 5$ ) and heavier ions.

[51] In Figure 8, extracted values of  $\delta D_n$  are plotted against the corresponding fraction of events passing the  $\Delta E_{56}$  cut. The two lines show the expected values. It is notable that at a cut value of 8 MeV, the surviving fraction comes closest to matching the prediction, and  $\delta D_n$  is also very close to the prediction. When the cut value is changed by  $\pm 1$  MeV,  $\delta D_n$  changes by  $\pm 13\%$ ; this seems to be a reasonable estimate of the uncertainty.

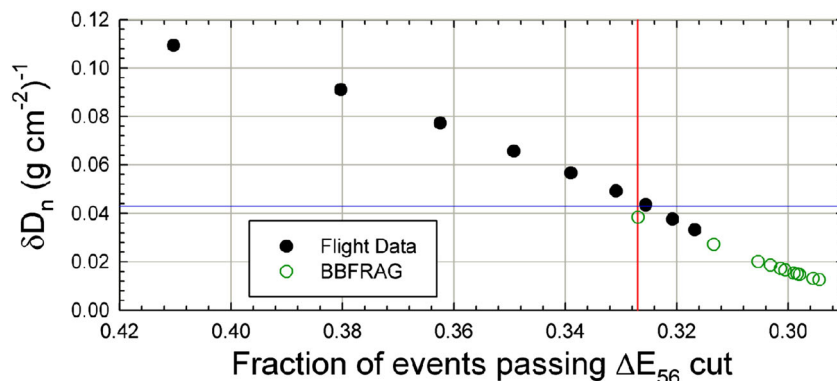
[52] Also shown in Figure 8 (green circles) are results obtained from BBFRAG. For this analysis, a new module was added to the code to simulate the incident angular distributions according to the method described by Sullivan [Sullivan, 1971]. In the model, every fragmentation reaction in the TEP produces one fragment, which is assumed to continue along the trajectory of the incident ion. With the smallest realistic value for the  $\Delta E_{56}$  cut, 0.3 MeV, the simulation gives precisely the fraction of surviving events we expect based on the geometry factor ratio. This is the leftmost green circle, at 0.327 on the  $x$  axis. The predicted value of  $\delta D_n$  is within 15% of the data value with a cut value of 8 MeV. As the cut on D5/D6 energy is increased in the simulation, the fraction of events quickly decreases, as does  $\delta D_n$ , with both having values smaller than any seen in the data.

#### 5.4. Dose Equivalent

[53] The sample of events selected for the above analysis consists of ions with relatively high energies. In this energy range,  $\Delta E/\Delta x$  in silicon can be related to linear energy transfer ( $\text{LET}_\infty$ ) in water, hereafter  $L$ , which is used to calculate tissue dose and dose equivalent (written  $H$ ). The subscript in  $\text{LET}_\infty$  refers to the concept of a detector volume of infinite size, which eliminates the effects of straggling and  $\delta$ -ray escape from a detector volume. In this hypothetical case, there is no difference between the mean and most probable energy deposits, i.e., one can use the mean energy loss given by the Bethe-Bloch equation to determine  $\text{LET}_\infty$ . It is then a matter of finding the constant of proportionality such that  $\Delta E/\Delta x$  in silicon as defined by the above calibration (which includes straggling) and cuts (which select the energy range of the ions) is converted to LET as accurately as possible. Using the



**Figure 7.** (top panel)  $\delta D_n$  and (bottom panel) the fraction of events surviving the  $\Delta E_{56}$  cut, both plotted against the cut value. The horizontal line in each plot corresponds to the expected values, as explained in the text.



**Figure 8.**  $\delta D_n$  versus the fraction of events surviving the  $\Delta E_{56}$  cut. The red line shows the expected fraction of events based on known geometry factors, while the blue line shows the expected  $\delta D_n$  value based on a fit to accelerator data.

simulation as a guide, we find that, to a good approximation,  $L = 0.63\Delta E/\Delta x$  for the event sample used here. Given the scale factor, we can calculate the average quality factor,  $\langle Q \rangle$ , as follows.

[54] 1. Histograms of  $L$  are made for D1/D2/D3/D4 (recall the same particle is required to be measured in both pairs) and for D5/D6.

[55] 2. The number of events in each histogram bin,  $N(L_i)$ , is multiplied by the average  $L$  in that bin, i.e., the value at the bin center  $L_i$ , to create a dose-weighted LET histogram.

[56] 3. Histograms of  $Q(L_i)$  as defined by [ICRP, 1991] are created.

[57] 4. The dose-weighted histograms are multiplied by the  $Q(L_i)$  histogram to create dose- and quality-weighted histograms.

[58] 5. The average quality factor is given by  $\sum_i N(L_i)L_iQ(L_i)/\sum_i N(L_i)L_i$ .

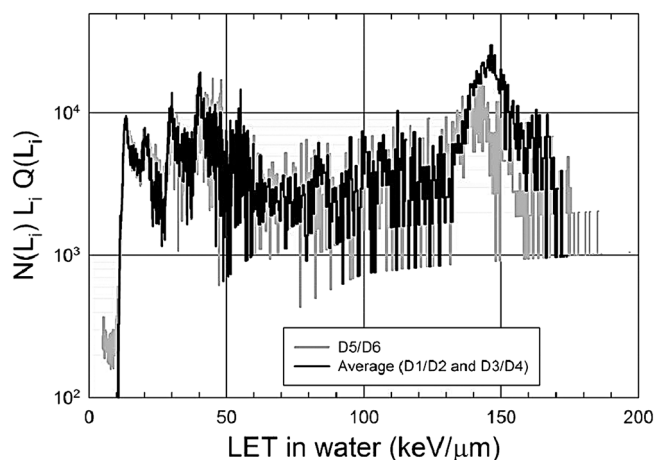
[59] Figure 9 shows fully weighted histograms, with the average LET in D1/D2 and D3/D4 shown in black, and D5/D6 shown in gray. Below 50 keV/ $\mu\text{m}$ , the thick detectors are used and the LET bins are narrow (1 keV/ $\mu\text{m}$ ). At higher LET, the thin detectors are used and the bins are four times wider.

[60] There are several interesting features in Figure 9. Most notably, in the “before” detectors (D1-D4), the broad peak of iron ions stands out above the peaks for other ions. This is a known effect of applying  $Q$  weighting to the GCR spectrum, and it accounts for the interest in high-energy iron in the radiation biology community [e.g., Durante *et al.*, 2002]. The iron peak is noticeably attenuated after TEP2, owing to fragmentation and a shift of some events to LET’s above the peak due to slowing down in TEP2. The low-LET events that are allowed in by the  $\Delta E_{56}$  cut are visible below the large peak of oxygen-ion events; these contribute very little to  $H$ . The rest of the LET spectrum, from 10 keV/ $\mu\text{m}$  to about 140 keV/ $\mu\text{m}$ , looks remarkably similar both before and after TEP2. Although fragmentation of all heavy ion species occurs in TEP2, it is most probable for iron, and fragments produced in iron

interactions re-populate the spectrum at lower LET, making up for some of the depletion that occurs when those lighter ions fragment.

[61] Another interesting aspect of Figure 9 is the enhanced clarity with which some of the ion peaks are seen. Going from low to high LET, peaks for O, Ne, Mg, and Si are clearly visible. A small peak around 54 keV/ $\mu\text{m}$  is consistent with the expected location of S ions ( $Z = 16$ ), and another near 83 keV/ $\mu\text{m}$  is consistent with Ca ( $Z = 20$ ). A broad peak in the upstream spectrum, centered around 165 keV/ $\mu\text{m}$ , is marginally consistent with being due to Ni ( $Z = 28$ ).

[62] The net loss of heavy ions after TEP2 (particularly Fe) results in a decrease in  $\langle Q \rangle$ . Upstream of TEP2, this data sample (O and heavier,  $\Delta E_{56} \geq 8$  MeV) has  $\langle Q \rangle = 13.5$ ; downstream of TEP2,  $\langle Q \rangle = 11.9$ . Thus, where dose after TEP2 was 87% of the incident dose, the dose equivalent is 77% of the incident  $H$ .



**Figure 9.** Dose- and quality-factor weighted LET (in water) spectra, for the first two detector pairs (black) and for D5/D6 (gray).

**Table 2.** Dose and Dose Equivalent Results From the OLTARIS Web Site for the GCR Environment 2010–2011

Shielding	Dose rate (mGy/day)	Dose Equivalent Rate (mSv/day)
None	0.329	2.10
3 g cm <sup>-2</sup> Tissue	0.349	1.79

[63] In the accelerator-based research to which we have been comparing, dose equivalent was not given much consideration, because the flux at the exit of a thin or moderately thick target is still dominated by surviving primary beam ions. Weighting by dose and  $Q$  almost invariably increases the relative importance of the surviving primary ions, so  $H$  is relatively insensitive to shielding in that context. The situation is different in space, where the flux of GCRs is more complex and no single ion species dominates.

### 5.5. Comparisons to OLTARIS Predictions

[64] Although it has proven useful in the above, the BBFRAG model was developed for simulation of beam line experiments, and has some limitations when simulating the space radiation environment. A helpful alternative is the OLTARIS Web site [Singleterry *et al.*, 2010] maintained by the NASA Langley Research Center. OLTARIS allows the user to specify GCR or SEP environments, and within those categories, to choose particular time frames, solar events, or (for GCR) values of the solar modulation parameter. Several shielding configurations are also available and custom configurations can be created. For comparison to CRaTER data with the data selection used here, we created a shield consisting of a sphere of tissue with a depth of 3 g cm<sup>-2</sup>, similar to TEP2. The Badhwar-O’Neill 2010 model [O’Neill, 2010] is used by OLTARIS to calculate the incident GCR fluxes, with the time period specified as 1 Jan 2010 to 1 Jan 2012. Table 2 shows results for dose and dose equivalent results obtained for free space (no shielding) and behind the tissue shield. The dose rate rises by about 6% over this depth; we will return to this point below. In contrast, the shield causes the dose equivalent rate to decrease, from 2.10 to 1.79 mSv/day, a 13% reduction. This is considerably less reduction than the 23% seen in the selected data, but this is because the OLTARIS results include all GCR ions over the full span of produced charges and energies, whereas selection cuts in the data produced a sample with high  $Z$  and high energy. A more detailed examination of the OLTARIS results is helpful on this point. The model predicts that iron ions contribute about 0.53 mSv/day in free space and about 0.32 mSv/day behind 3 g cm<sup>-2</sup> of tissue; thus the shield produces a 39% reduction in  $H$  from iron. (Note that the difference is 0.21 mSv/day, or 10% of the free-space total.) Silicon—the species that makes the second largest contribution to  $H$  in free space—contributes 0.21 mSv/day in free space and 0.15 mSv/day behind the shield, a 28% reduction. Of course, these simple checks ignore the secondaries

produced by these primary ions, and therefore overestimate the shielding effect. Even so, the 23% decrease seen in the selected data appears to be at least roughly in line with OLTARIS predictions.

[65] The difference in the results for dose in the data versus OLTARIS can be explained qualitatively by considering the lower-energy GCR ions that are specifically excluded by the selection cuts in the data. Many of these slower ions have sufficient energy to fully penetrate the CRaTER stack, and, because of the  $Z^2/\beta^2$  dependence of energy loss, have higher LET when they reach the second or third detector pair than they did in D1/D2. The increase in dose from this effect tends to offset the decrease caused by fragmentation. As the model indicates, dose rate can go up with depth if this “slowing down” effect outweighs the effect of fragmentation. The two effects are in competition, and the relative importance of each depends on the energy distribution of the incident particles. By selecting high-energy ions in the analysis, we intentionally chose a subset for which fragmentation is the more important effect. There is an additional difference between the above data analysis and the OLTARIS predictions: the data shown here exclude protons, which are included in OLTARIS. Protons contribute significantly to dose, less so to dose equivalent. Protons cannot fragment into lighter ions, but some do slow significantly in TEP, increasing the dose per particle downstream of the shielding. Protons can also produce high-LET secondaries. Thus dose due to incident protons tends to be larger behind shielding than it is upstream of the shielding.

[66] Changes in dose equivalent caused by shielding are more complicated than changes in dose. Following along the lines of the argument for dose, we might expect the decreased velocity of slower ions after passing through TEP to drive dose equivalent up in the range between 10 and 100 keV/ $\mu$ m, since  $Q(L)$  increases monotonically in this range. However,  $Q(L)$  decreases monotonically above 100 keV/ $\mu$ m, which mitigates the effect. Further, as mentioned above, the unique role of iron ions must be considered. A kinetic energy greater than 250 MeV/nuc is required for a <sup>56</sup>Fe ion to pass through 3 g cm<sup>-2</sup> of TEP. From the Badhwar-O’Neill GCR model, we find that this means about 18% of the iron flux will simply stop in the TEP. Based on known cross sections, an additional 25% can be expected to fragment into lighter ions in the same depth. Thus more than 40% of GCR iron ions do not survive even this modest amount of shielding intact. These effects alone reduce the dose equivalent by about 10%, as noted above.

## 6. Conclusions

[67] The unique design of the CRaTER telescope, with its incorporation of tissue-equivalent plastic, allows for tests of shielding effectiveness of tissue-like material in space where they are exposed to the full GCR. But the presence of the TEP layers also leads to difficulties in the data analysis, arising largely from  $\delta$ -ray production by

high-energy ions. As a result, there is no way to select an event sample with well-defined geometry, and model predictions must be used to guide the interpretation of the data.

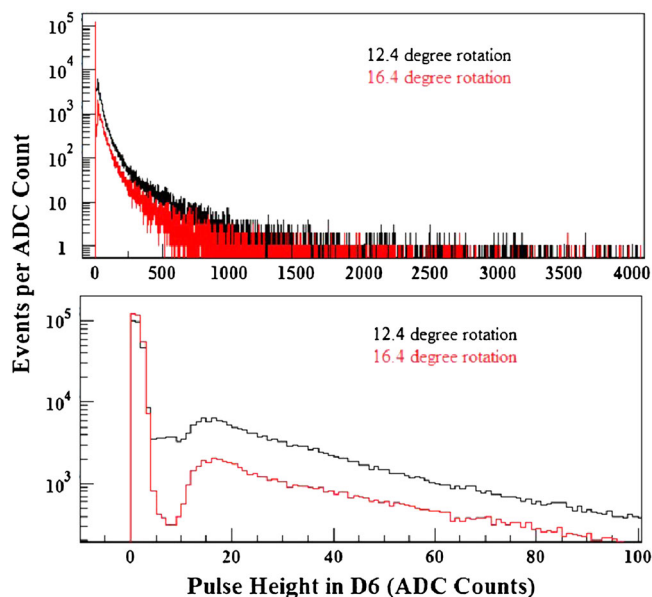
[68] The shielding results can be summarized as follows. If we make a selection cut on  $\Delta E_{56}$  such that the number of events in the sample agrees with the number expected from the ratio of the D2-D4-D6 and D2-D4 geometry factors, we obtain a  $\delta D_n$  value of  $0.044 \pm 0.006$  ( $\text{g cm}^{-2}$ )<sup>-1</sup>, where the uncertainty reflects reasonable changes in the cut. The central value agrees well with predictions from both accelerator-based data and our simple BBFRAG Monte Carlo simulation. The 23% reduction in dose equivalent seen with this same selection is also reasonably close to the 20% prediction obtained from OLTARIS for the full GCR spectrum.

[69] The results are encouraging, but should be viewed with caution. Excluding events with relatively small  $\Delta E_{56}$  from the sample biases  $\delta D_n$  towards a smaller value, while the inclusion of out-of-cone events shifts  $\delta D_n$  in the other direction. At some value of the  $\Delta E_{56}$  cut, the two effects balance. Further work is needed to fully understand these effects. On the modeling side, we expect that a full GEANT4 simulation that includes nuclear fragmentation and  $\delta$ -ray production will clarify matters. On the data side, we have recently obtained beam data with high-energy heavy ions beams that will shed additional light on the underlying physics. Analysis of that data is in progress; an initial look at the data is presented in Appendix A.

## Appendix A: Beam Tests of Out-of-Cone Triggers

[70] To test the hypothesis that coincidence triggers (D2-D4 or D2-D4-D6) may fire even when a primary ion is outside the nominal viewing cone, an engineering model CRaTER instrument was taken to the Heavy Ion Medical Accelerator in Chiba (HIMAC) for a series of experiments. The engineering model is, for all practical purposes, an identical copy of the flight model. A more detailed and quantitative analysis of the beam data will be presented in the future, but for present purposes, we show examples that confirm our initial hypothesis. Four beams were used: 160 MeV<sup>1</sup>H, 180 MeV/nuc <sup>4</sup>He, 800 MeV/nuc <sup>28</sup>Si, and 500 MeV/nuc <sup>56</sup>Fe. The data shown here were acquired with the <sup>28</sup>Si beam.

[71] The CRaTER instrument was placed in the beam hall on a rotating stage that was remotely controlled. The mounting arrangement allowed for two centers about which the instrument could be rotated with respect to the direction of the incoming beam, which is small (typically on the order of 1 cm in diameter) and highly parallel. Both rotation points were along the detector's central axis, one at the mid-point between D1 and D2, the other at the mid-point between D5 and D6. Here, we show data taken with CRaTER rotated about the D1/D2 mid-point. When the angle between the central axis of CRaTER and the beam axis exceeds 8°, particles traveling along the beam axis should miss D6, except for rare large-angle Coulomb



**Figure A1.** Pulse height distributions in D6 for beam data with 800 MeV/nuc <sup>28</sup>Si ions with incident trajectories outside the D6 field of view. (top panel) Full-scale histograms for 12.4° (black) and 16.4° (red) rotations. (bottom panel) Same histograms, zoomed in on the region of small pulse heights.

multiple scattering. Considering the finite extent of the beam and possible small errors in positioning, we chose to examine data taken at rotation angles somewhat larger than 8°. Pulse height distributions in D6 are shown in the two panels of Figure A1, for 12.4° (black histograms) and 16.4° (red histograms) rotations. Figure A1(top panel) shows the full range of pulse height, the Figure A1(bottom panel) zooms in on the low end. The number of incident primary ions was about  $5 \times 10^5$  for the 12.4° data and about  $4 \times 10^5$  for the 16.4° data.

[72] The two D6 pulse height distributions are qualitatively similar. Both show large peaks near 0 and long tails to the high end. The portion of the distribution above about 1000 ADC counts is populated by ions scattered at large angles. Below 1000 ADC counts, it is not possible to identify the particles that traverse the detector; presumably, they are a mixture of  $\delta$ -rays, projectile fragments, and target fragments. In Figure A1(bottom panel), both distributions show large spikes of events with pulse heights below 10 ADC counts; these can be considered zero energy deposition in D6. In the 12.4° data, these amount to 57% of the total number of events, and in the 16.4° data, 80%. Naively, one would have expected the fraction in both cases to be very close to 1.

[73] These data confirm the hypothesis developed from flight data that particles well outside the nominal viewing cones can generate unexpected coincidences. This has important implications for many aspects of CRaTER data analysis.

[74] **Acknowledgments.** This work was supported by Southwest Research Institute under Agreement 12-053 with the University of New Hampshire, and by the University of New Hampshire under the NASA CRaTER contract NNG11PA03C.

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