Proceedings of ICRC 2001: 1445 © Copernicus Gesellschaft 2001

ICRC 2001

Space based calorimeters: Heavy ion simulations

J. Z. Wang[1], E. S. Seo[1], H.S. Ahn[1], R. W. Alford[1], O. Ganel[1], Y. J. Han[2], H. J. Kim[2], K. C. Kim[1], S. K. Kim[2], I. M. Koo[2], Y. I. Kwon[2], M. H. Lee[1], R. Sina[1], and J. Wu[1]

[1]IPST, University of Maryland, College Park, MD 20742, USA
[2]Seoul National University, Seoul, South Korea

Abstract. The Advanced Cosmic-ray Composition Experiment for the Space Station (ACCESS) is baselined with an ionization calorimeter for high-energy cosmic ray composition measurements. We have developed GEANT-based simulation models of the instrument to study its performance. The original GEANT code was developed primarily for accelerator colliding proton beam experiments, and doesn't handle incident nuclei heavier than protons. To study the detector response to $Z > 1$ cosmic rays, we thus had to develop a separate code for heavy ion interactions and fragmentation, to be interfaced with GEANT. Below we present results of our simulations of the ACCESS baseline calorimeter response to heavy ions.

1 Introduction

The ACCESS mission will measure the energy spectra of individual elements from hydrogen to iron in cosmic radiation approaching the knee region (Gaisser et al., 1998), which is crucial for understanding the acceleration limit in supernova blast waves. The baseline design of ACCESS shown in Fig. 1 employs a Charge Identification Module (CIM), a Transition Radiation Detector (TRD) and a thin calorimeter to measure the charge, velocity and energy of cosmic rays with energies up to approximately 10^{15}eV. For heavy ions ($Z \geq 3$) within both the TRD and calorimeter aperture, the TRD measures the Lorentz factor by determining the yield of transition radiation, and the calorimeter measures the energy deposit of the showers initiated by them. The unique combination of detectors provides a direct cross calibration of both detectors for a subset of nuclei in an energy region which is inaccessible by terrestrial accelerators in the near future.

To study the calorimeter showers initiated by heavy ions, several event generators for relativistic ion interactions, FRITIOF, RQMD etc., were implemented and interfaced with the widely used simulation package GEANT (Brun et al., 1984). Refer to Kim et al. (1999) for the detailed procedure and a comparison with accelerator data. In this paper, we present results of our simulations of the ACCESS baseline calorimeter response to heavy ions.

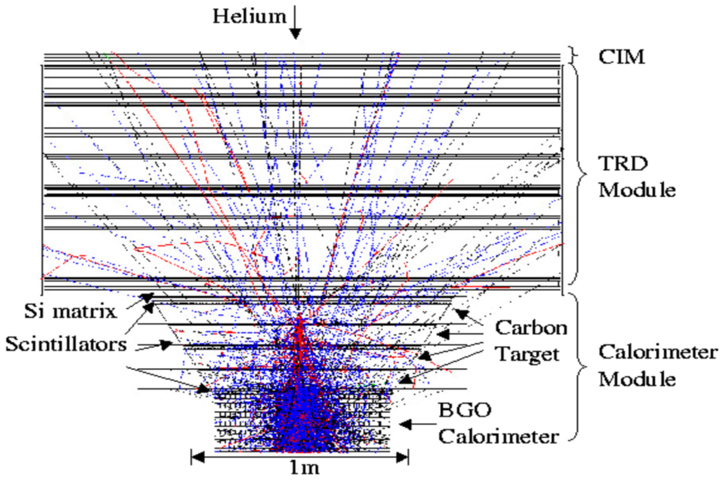

Fig. 1. Cross-sectional view of the ACCESS baseline configuration. Overlayed is a simulated 500 GeV He event.

2 ACCESS Baseline

Figure 1 illustrates the ACCESS Baseline configuration. The CIM is similar to the Silicon detector sitting directly above the calorimeter target. Both are silicon matrices with suitable pixel size to distinguish the charge of the primary cosmic ray from the abundant back-splash particles associated with calorimeter showers. The TRD consists of six layers of radiators plus proportional tubes to record the TR signals, with scintillators for triggering the subsystem. The calorimeter includes a one interaction-length thick target of inert carbon followed by a Bismuth Germanate (BGO) calorimeter with

---

Correspondence to: J. Z. Wang (jzwang@glue.umd.edu)

laterally oriented crystals in crossed layers. The thickness of the BGO is 27 radiation lengths which will provide an energy resolution better than 35% over the entire energy range of ACCESS. The scintillators in the calorimeter module provide a fast event trigger and some additional information, i.e., charge measurement to supplement the Si matrix and tracking information in addition to BGO crystals. The calorimeter Si matrix provides charge measurements even for many events which do not pass through the CIM module.

The TRD has a large geometry acceptance of 8 m^2sr. The calorimeter is designed with optimized target shape and mass allocation between the carbon target and the BGO crystals. The raw geometry factor of the calorimeter is 0.91 m^2sr. The overall interaction probability for protons within the geometry is about 70%, increasing with higher incident charge to near 100% for Fe nuclei. About 63% of calorimeter events (0.57 m^2sr) will pass through the CIM and the entire TRD, and those events could be used to cross calibrate both instruments. Assuming the power law spectra of proton, helium and all particles (Wiebel et al., 1998) measured at low energies can be extended to 1 PeV (10^{15}eV) and above, the calorimeter is expected to detect at least 10 protons, 30 helium nuclei and 45 heavy nuclei ($Z \geq 3$) with energy above 1 PeV.

3 Simulation

3.1 Heavy ion simulation in the GEANT framework

The GEANT code (Brun et al., 1984) was developed primarily for accelerator colliding proton beam experiments. Since GEANT does not accommodate the simulation of heavy ions, we have interfaced GEANT with the hadronic simulation packages FRITIOF/RQMD for heavy ion simulation (Kim et al., 1999). FRITIOF (Andersson, 1993) is based on semi-classical considerations of string dynamics for high energy hadronic collisions. RQMD (Relativistic Quantum Molecular Dynamics) was adopted for our simulations of heavy ions for energies in the center-of-mass frame less than 10 GeV/nucleon. RQMD is a semi-classical microscopic approach which combines classical propagation with stochastic interactions, and it successfully describes the available single-particle spectra at the AGS and CERN (Sorge, 1995).

To adapt GEANT for heavy ion simulations, two interfaces were made. One was to implement the NASA Langley Research Center (LaRC) model (see next subsection) for determining interaction probabilities for heavy ions. The second was to embed FRITIOF/RQMD into GEANT to perform heavy ion fragmentation.

3.2 Nuclear interaction probability

Our simulations required cross sections covering various target materials from low Z to high Z (e.g. carbon, aluminum, scintillator (hydrogen), and BGO) with heavy ion beams in the energy range from tens of GeV to above 1 PeV. The LaRC parameterization method was introduced for this purpose. This model, developed by Tripathi et al. (1996), is a universal parameterization method for reaction cross sections, and can be used for any system of colliding nuclei. In the LaRC model, the reaction cross section σ_R can be expressed by the formula

$$\sigma_R = \pi r_0^2 \left(A_P^{1/3} + A_T^{1/3} + \delta_E \right)^2 (1 - B/E_{cm}) , \qquad (1)$$

where r_0 = 1.1 fm, A_p and A_t are respectively the projectile and target mass numbers, and E_{cm} is the colliding system center-of-mass energy. The δ_E term represents two effects: transparency and Pauli blocking at intermediate and higher energies. The last term is the Coulomb interaction term with B representing the energy-dependent Coulomb barrier. We have compiled experimental cross section data for deuterons, and helium nuclei and have used them to tune the LaRC model. Refer to Wang et al. (1999, 2001) for a detailed discussion.

Table 1 summarizes the interaction fractions of vertically incident protons, He, C and Fe at different instrument depths. A large number of events, more than half in the case of Fe, interact inside the TRD or CIM modules. An algorithm to identify particles interacting in the TRD but not passing through the CIM has been developed (Wang et al., 2000), and the data are being analyzed with this algorithm.

Table 1. Fraction of events with first interactions in different modules.

Modules	CIM	TRD	Carbon target	BGO calorimeter
p	0.005	0.12	0.61	0.19
He	0.009	0.22	0.71	0.05
C	0.02	0.35	0.63	0.
Fe	0.04	0.60	0.36	0.

4 Results and Discussion

4.1 Energy response and resolution

Using the simulation code developed for this study, we have simulated the energy response and resolution of the ACCESS baseline instrument for several abundant cosmic-ray heavy ions with energies from 100 GeV to 10 TeV. Figure 2 shows the distribution of energy deposition of 1 TeV protons, He, C and Fe as simulated using the FRITIOF complete fragmentation model. Only events first interacting in the carbon target were selected. The mean energy deposition (E_m) is about 46% of the primary energy for protons. This fraction is slightly smaller for heavier ions and is about 36% for 1 TeV Fe nuclei. This is due to the fact that heavier ions have more ionization energy loss in the detector materials above the BGO calorimeter, and that some nucleons from the complete fragmentation of heavy nuclei pass through the calorimeter without further interaction. As shown in Fig. 3,

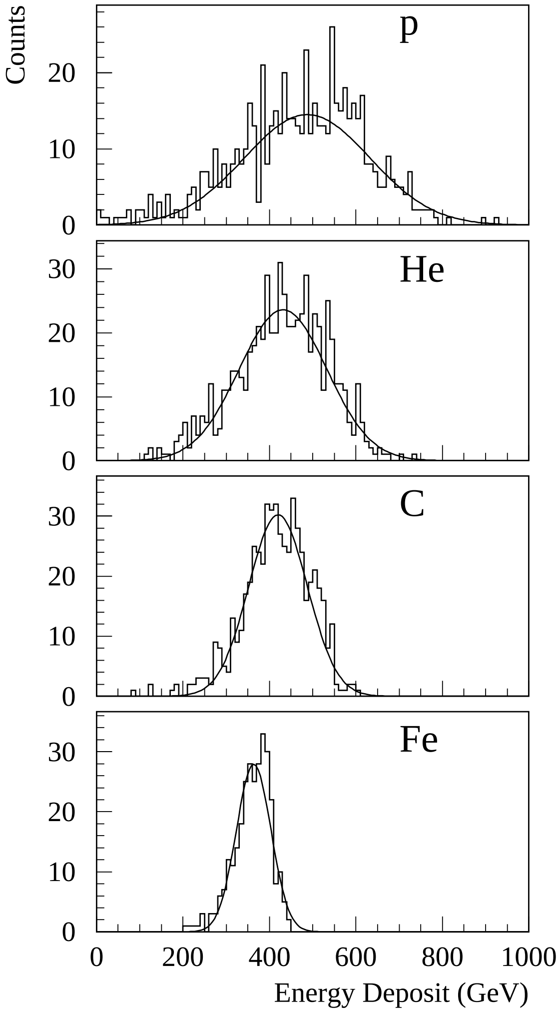

Fig. 2. Energy deposition in the BGO calorimeter for 1 TeV protons, He, C and Fe respectively.

the energy dependence of the mean energy deposition is almost linear over the entire simulated energy range. The energy resolution (σ/E$_m$, where σ is the standard deviation of the energy deposit distribution) is presented in Fig. 4 for protons, He, C and Fe. The heavy ion energy resolution is much better than that for protons (about 32%), improving with increasing atomic number.

4.2 Complete fragmentation vs. minimum fragmentation

Two different fragmentation models were considered in FRITIOF: (1) complete fragmentation, and (2) minimum fragmentation. The complete fragmentation model is similar to the superposition model. The incident nucleus is fragmented completely into individual nucleons during the first hadronic interaction with the detector. In the minimum fragmentation model, some nucleons are knocked out from the incident heavy ion during each interaction, and the residual nucleus remains intact as a single fragment. Nucleons in light ions, such as He, behave much like free nucleons. Figure 5(a) shows that both models produce similar results for 1 TeV helium nuclei. When the mass number increases, the nucleons are bound together more tightly. The minimum fragmentation model employed here underestimates the degree of nuclear interactions, so the simulated calorimeter leakage has larger fluctuations than experimentally observed. Figure 5(b) indicates a difference in the energy deposit of incident carbon nuclei for the two models: specifically, as expected, mini-

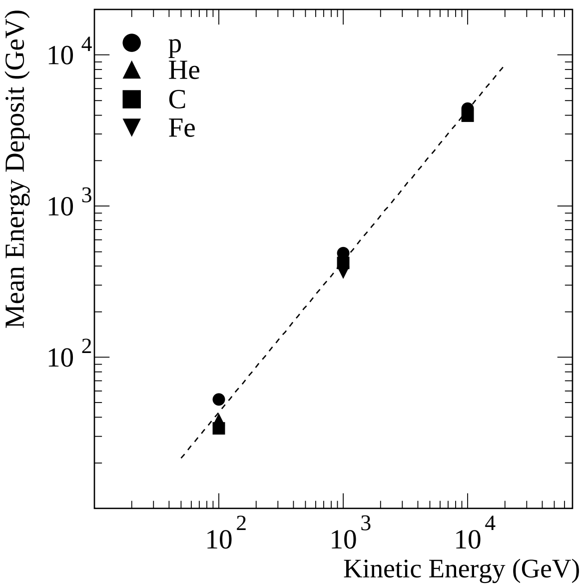

Fig. 3. Energy dependence of the mean energy deposition for protons (circles), He (upward pointing triangles), C (squares) and Fe (downward pointing triangles).

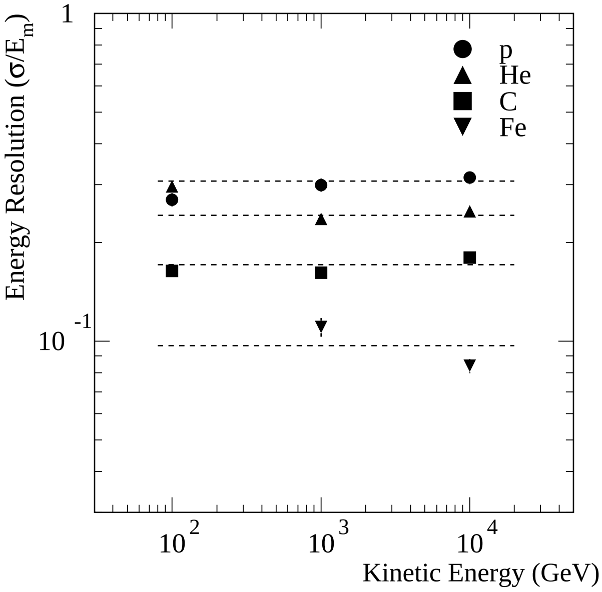

Fig. 4. Energy dependence of the energy resolution for protons (circles), He(upward pointing triangles), C (squares) and Fe (downward pointing triangles).

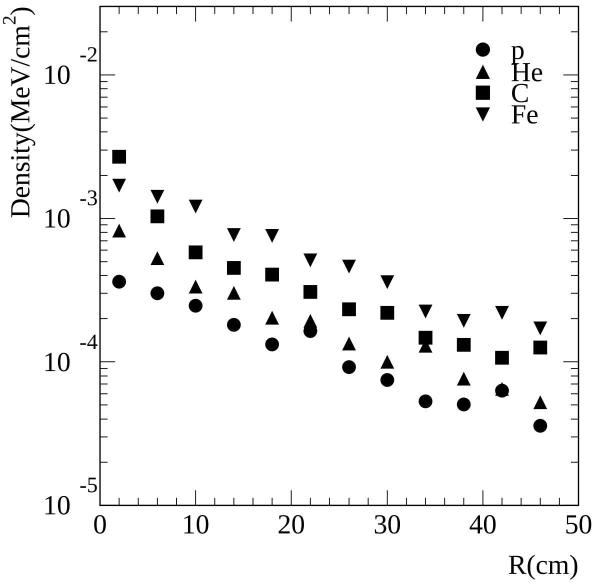

Fig. 5. Mean backscattered energy density in the Silicon detector at the top of the calorimeter as a function of distance from the primary trajectory. The data points are as follows: circles, protons; upward pointing triangles, He; squares, C; and downward pointing triangles, Fe.

mum fragmentation shows larger fluctuations than complete fragmentation. The actual energy response and resolution of heavy ions should be between the estimates from these two models.

4.3 Backscatter effect

During the cascade simulations, we kept track of the backscattered particles from the BGO calorimeter/carbon target and studied how these albedo particles can affect the primary charge measurements. In order to study this effect, their contribution to the energy deposit in the charge detectors was distinguished from the ionization loss of the primary particle. Figure 6 plots the mean back-scattered energy deposit density (in MeV/cm^2) in the Si matrix at the top of the calorimeter as a function of the distance from the incident primary trajectory. The incident energy is 1 TeV for all four species. These data are obtained from events interacting in the carbon target. The figure shows the gradual rise of backscatter energy density with the primary atomic numbers as expected. Since the energy deposit of the primary particles is proportional to Z^2, and most of the albedo charged particles are relativistic (several MeV) electrons that result from back-scattered gamma rays, the influence on the charge measurement for high-Z primaries is much smaller than it is for primary protons.

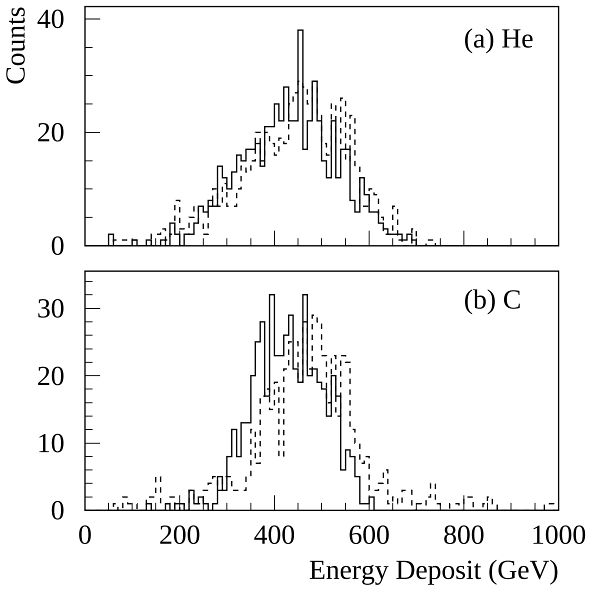

Fig. 6. Energy deposition in the BGO calorimeter for 1 TeV (a) He and (b) C nuclei. Solid lines represent complete fragmentation and dashed lines represent minimum fragmentation.

Acknowledgements. This work was supported by NASA grants NAG5-5155 and NAG5-5204.

References

Andersson, B., Gustafson, G., & Pi, H. 1993, Z. Phys. C, 57, 485
Brun, R., et al. 1984, GEANT User's Guide, CERN DD/EE/84-1 (Geneva)
Gaisser T. K. et al. 1998, The European Physical Journal C3, 132.
Kim, H. J., et al. 1999, Proc. 26th ICRC (Utah, 1999), 1, 17
Sorge, H. 1995, Phys. Rev. C, 52, 3291 and reference therein
Tripathi, R. K., Cucinotta, F. A. & Wilson, J. W. 1996, Nucl. Instr. Meth. B, 117, 347
Wang, J. Z., et al. 1999, Proc. 26th ICRC (Utah, 1999), 3, 37
Wang, J. Z., et al. 2000, Bulletin of the APS, 45, 2, 54
Wang, J. Z., et al. 2001, ApJ, (submitted)
Wiebel-Sooth B., Biermann P. L. & Meyer H., 1998, A&AS, 330, 389