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A detailed FLUKA-2005 Monte-Carlo simulation for the ATIC detector

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Abstract

We have performed a detailed Monte-Carlo (MC) simulation for the Advanced Thin Ionization Calorimeter (ATIC) detector using the MC code FLUKA-2005 which is capable of simulating particles up to 10 PeV. The ATIC detector has completed two successful balloon flights from McMurdo, Antarctica lasting a total of more than 35 days. ATIC is designed as a multiple, long duration balloon flight, investigation of the cosmic ray spectra from below 50 GeV to near 100 TeV total energy; using a fully active Bismuth Germanate (BGO) calorimeter. It is equipped with a large mosaic of silicon detector pixels capable of charge identification, and, for particle tracking, three projective layers of *x*–*y* scintillator hodoscopes, located above, in the middle and below a 0.75 nuclear interaction length graphite target. Our simulations are part of an analysis package of both nuclear (A) and energy dependences for different nuclei interacting in the ATIC detector. The MC simulates the response of different components of the detector such as the Si-matrix, the scintillator hodoscopes and the BGO calorimeter to various nuclei. We present comparisons of the FLUKA-2005 MC calculations with GEANT calculations and with the ATIC CERN data.

Keywords: Scientific ballooning; ATIC long duration balloon project

1. Introduction

High energy cosmic rays, particles of matter from distant regions of our galaxy and possibly elsewhere in the universe, can be directly observed by balloon-borne or space-based experiments. Understanding the cosmic ray composition and energy spectra can provide clues to the origin of cosmic rays, their acceleration mechanism, and their propagation through the galactic and intergalactic media. Cosmic rays contain all natural elements from proton to nuclei beyond nickel. The all-particle spectrum of cosmic rays (where species can not be distinguished) obeys a power law dependence of the observed flux on energy from 10 GeV up to the highest energies measured by

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ground-based air shower array experiments, over 10^{20} eV. From these measurements, it is known that the spectrum is somewhat steeper above 10^{16} eV than it is below 10^{14} eV. This steepening is called the "knee". It is not known whether this knee is due to:

- a change in the propagation of cosmic rays;
- a change in the acceleration mechanism of cosmic rays;
- a change in the composition of the cosmic rays.

The Advanced Thin Ionization Calorimeter (ATIC) is a balloon-borne experiment designed to investigate the elemental spectra of protons and other nuclei up to $Z = 26$, for energies from 50 GeV to 100 TeV, with a statistical accuracy of better than 30% for protons at the highest energy (Guzik et al., 1999). The ATIC balloon payload was launched to an altitude of 36 km above sea level from McMurdo, Antarctica in December 2000 and December 2002. The total of these two flights lasted more than 35 days.

In this paper, we discuss a data analysis tool we have developed based on FLUKA-2005. This code provides the capability of simulating high energy interactions well beyond 100 TeV, the highest energy measured by the ATIC detector.

2. Scientific objectives

The ATIC detector focuses on direct measurements of high energy cosmic rays. The main scientific objectives of the ATIC experiment are:

- to measure the H and He energy spectrum from $\approx 10^{10}$ eV to $\approx 10^{14}$ eV with a single instrument;
- to investigate the spectral differences between protons and helium;
- to determine if the proton spectrum has a bend between 2 TeV and ≈40 TeV;
- to accurately measure the H/He ratio as a function of energy;
- to determine if the spectra of heavy nuclei have the same indices;
- to search for high-energy electrons and neutrals.

3. ATIC detector

The ATIC detector shown in Fig. 1 is comprised of a fully active 50 cm × 50 cm × 20 cm deep BGO calorimeter, preceded by three 10-cm thick graphite targets sandwiched between panels of scintillator hodoscopes, having an outwardly projective angle of 24°. It is equipped at the top with a large mosaic of silicon detector pixels capable of charge identification. The BGO crystals of dimensions 2.5 cm × 2.5 cm × 25.0 cm long are arranged horizontally in eight layers, with the long axis aligned alternately along the *X* and *Y* axes. The vertical direction is along the *Z*-axis.

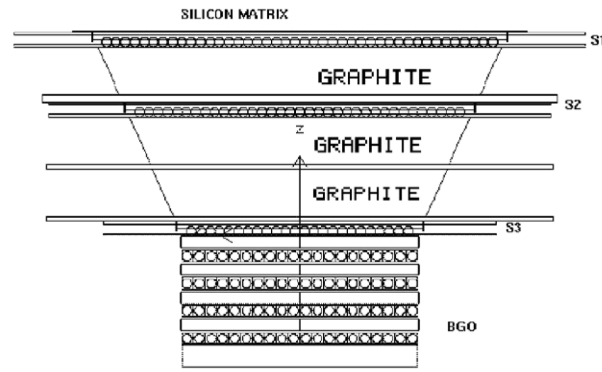

Fig. 1. ATIC detector, showing the Si-matrix, the three scintillator hodoscopes S1, S2, and S3, the graphite targets and the BGO calorimeter.

There are 320 BGO crystals with 40 crystals in each layer. The construction and commissioning of the detector, the data acquisition system and the software development for the detector, and detector calibration are discussed elsewhere (Guzik et al., 1999).

4. GEANT-3.21 ATIC Monte-Carlo

We have written a MC code for the ATIC detector using GEANT-3.21, that generates events with energies less than 20 TeV. Note that GEANT-3.21 is presently limited to energies below 20 TeV for hadrons. Fig. 1 was generated by GEANT-3.21 using a geometry input file for the ATIC detector.

In 1999, the ATIC detector was calibrated using test beams at CERN. The detector was illuminated with 375 GeV protons, 300 GeV electrons, 150 GeV electrons and 150 GeV pions. Fig. 2 shows the energy spectra from data and MC simulations for 375 GeV protons. The data

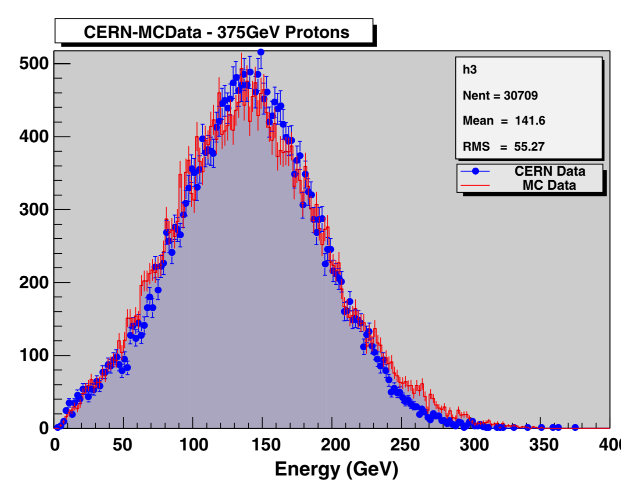

Fig. 2. Comparison of CERN 375 GeV proton data with GEANT. The mean value and the RMS value for MC data (Red line) are 141.64 and 55.27, respectively. The mean value and the RMS value for CERN data (Blue line) are 138.36 and 50.35, respectively. (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

and the simulated results agreed well as expected. Figs. 3 and 4 show the comparison of data for 150 GeV protons and pions with our GEANT3.21 MC calculations. Note the MC calculations have been performed for the same number of events as the data.

GEANT is widely used in high energy physics for the simulation of primary particles such as p, e, and μ. When GEANT4 was introduced the support for GEANT-3.21 became limited. GEANT4 is evolving very rapidly but it still has some limitations for simulations at very high energies (TeV to PeV range) and cannot provide simulations of heavy ions.

One of the primary goals of ATIC is to determine the indices for the energy spectrum of heavy ions from He, C, N, O to Fe up to very high energies. For this purpose we had to find a reliable simulation code to simulate heavy ions. After a thorough search, we decided to use FLUKA.

5. Description of the FLUKA code

FLUKA which stands for "FLUktuierende KAskade" is a MC code able to simulate the transport and interaction of hadronic and electromagnetic particles on any target material. It is a multi-particle, multipurpose code and is used in many different fields such as medical physics, astrophysics and high energy physics (Fasso' et al., 2003). It has been tested and verified with real data. For light nuclei, it uses the Fermi break model. Above 5 GeV/nucleon, the Dual Parton Model (DPM) is used. FLUKA can treat combinatorial geometry. It is widely used for studies related to both basic research and to applications in radiation propagation, dosimetry, cosmic ray, and accelerator physics. Followings are a few areas to which modern FLUKA has been successfully applied (Ferrari, 2005).

- Accelerators and shielding – CERN, SLAC;
- Background and radiation damage studies- ATLAS and LHC experiments;
- Dosimetry and radiotherapy – NASA;
- Calorimetry – ATLAS test beams and ICARUS neutrino experiment.

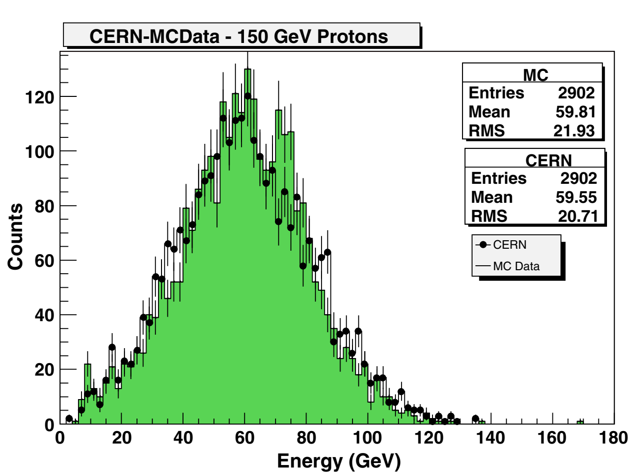

Fig. 3. Comparison of CERN 150 GeV proton data with GEANT.

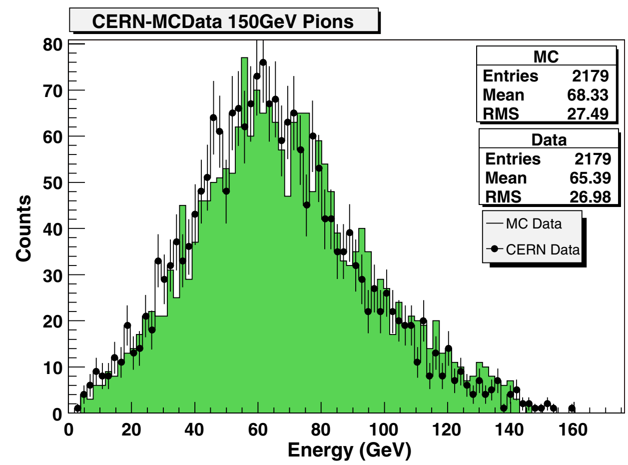

Fig. 4. Comparison of CERN 150 GeV pion data with GEANT.

One of the main reasons for using FLUKA for ATIC is the ability to transport heavy ions at very high energies. FLUKA is designed to transport heavy ions and their interaction products from 5 GeV/nucleon to very high energies, approximately 10 PeV, using a DPMJET-3 code which is a high energy hadron–hadron, hadron–nucleus, nucleus–nucleus interaction model. It can run on various platforms such as Linux, Unix and HP. The validity of the models implemented in FLUKA have been benchmarked against several experimental data, from accelerators to cosmic ray showers (Fasso' et al., 2003). The FLUKA code is maintained and updated regularly. The FLUKA discussion archive provides much support for the FLUKA user community (http://www.fluka.org).

6. The ATIC-FLUKA code

We implemented the ATIC geometry in the FLUKA code. Events were randomly generated in position, direction and energy above the Si-matrix plane. An energy dependence of $E^{-2.7}$ was assumed. Fig. 5 shows a 150 GeV proton vertically incident on ATIC very close to the center on top of the detector.

We have compared the energy deposition in the ATIC BGO calorimeter using GEANT-3.21 and FLUKA. Fig. 6 shows this comparison. Fig. 7 shows the comparison of energy deposition by 1.0 TeV protons in ATIC. Fig. 8 shows the energy distributions obtained from FLUKA and CERN data for 375 GeV protons incident on ATIC. Although at lower energies the agreement between GEANT and FLUKA and CERN data are good, at higher energy, namely 1.0 TeV, there is a 10% discrepancy in the mean energy deposit of GEANT and FLUKA. Because no beam-test data are available at 1.0 TeV for ATIC, it is not clear which simulation is better.

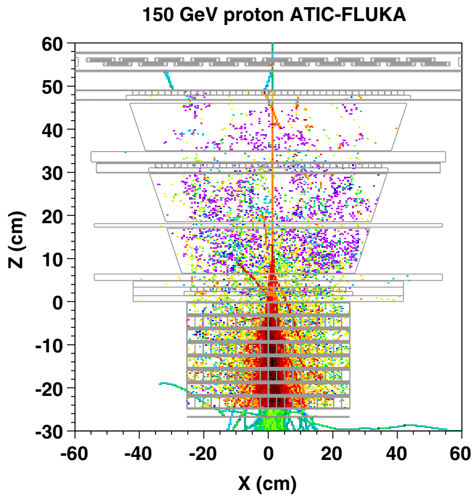

Fig. 5. A 150 GeV proton interacting in the ATIC detector. Colors in the plot denote different densities of energy deposit in the detector. The order of colors from maximum to minimum energy density are black, red, orange, yellow, green, blue, and purple. (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

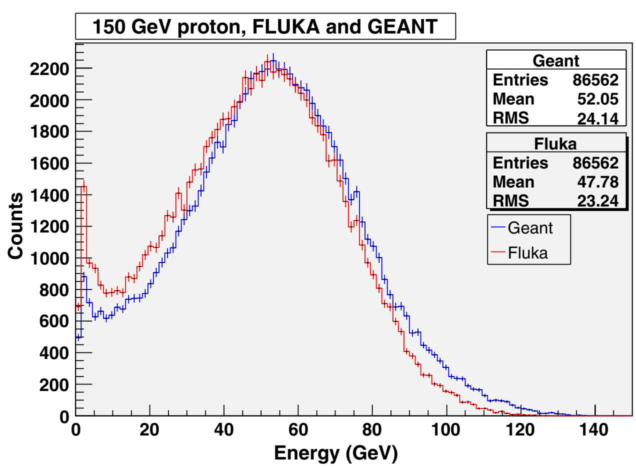

Fig. 6. Comparison of the deposited energy spectra in the BGO calorimeter for 150 GeV protons from GEANT and FLUKA calculations.

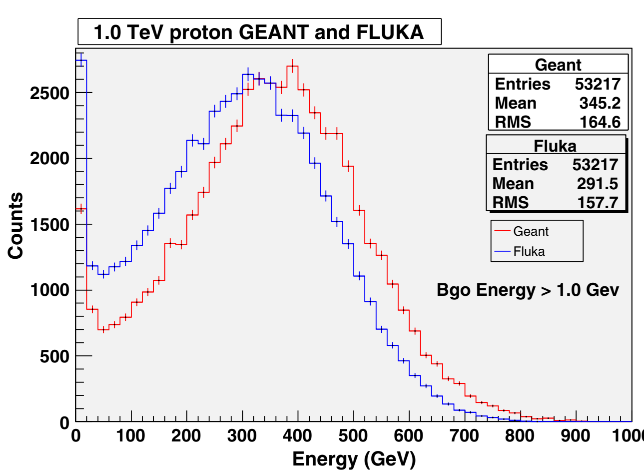

Fig. 7. Comparison of the deposited energy spectra in the BGO calorimeter for 1.0 TeV protons from GEANT and FLUKA calculations.

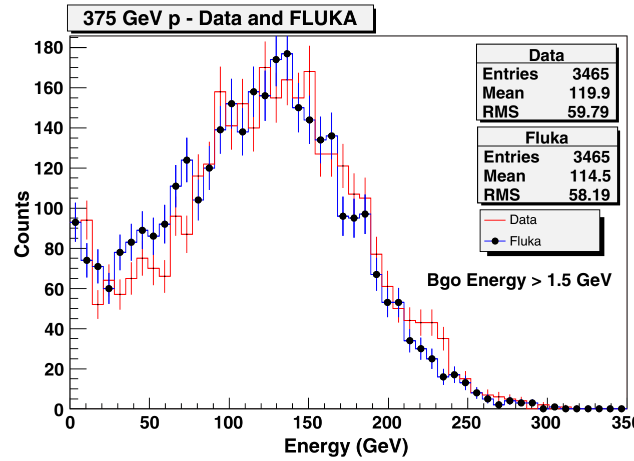

Fig. 8. Comparison of the deposited energy spectra in the BGO calorimeter for 375 GeV protons from CERN data and FLUKA calculations.

7. Heavy ion simulation

One of the primary goals of ATIC is to determine the indices for the energy spectra of nuclei such as He,C,N,O up to Fe. For this purpose, we implemented the DPM-JET-3 interface to the FLUKA input card file. Fig. 9 shows a 12 TeV ^{12}C nucleus vertically incident on ATIC close to the center of the detector.

Fig. 10 shows an event display for a 40 TeV ^{14}N nucleus incident on ATIC with a randomly chosen position and direction. Fig. 11 shows a 64 TeV ^{16}O nucleus entering the top of the detector with a randomly chosen position and direction.

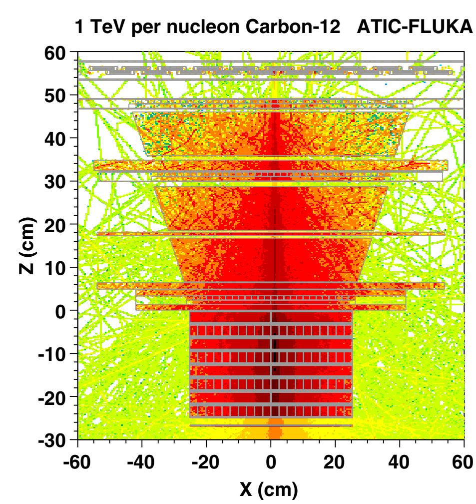

Fig. 9. A 12 TeV ^{12}C nucleus interacting in the ATIC detector. Colors in the plot denote different densities of energy deposit in the detector. The order of colors from maximum to minimum energy density are black, red, orange, yellow, green, blue, and purple. (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

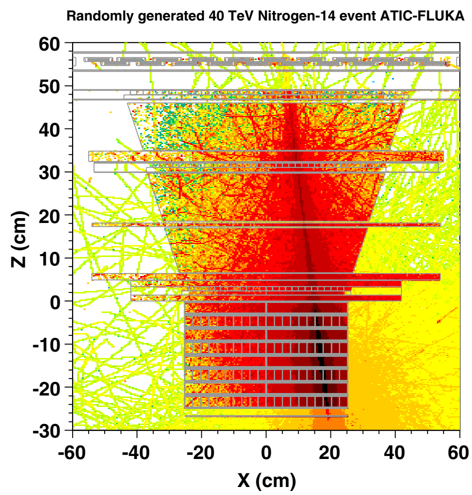

Fig. 10. A 40 TeV ^{14}N nucleus interacting in the ATIC detector. Colors in the plot denote different densities of energy deposit in the detector. The order of colors from maximum to minimum density are black, red, orange, yellow, green, blue and purple. (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

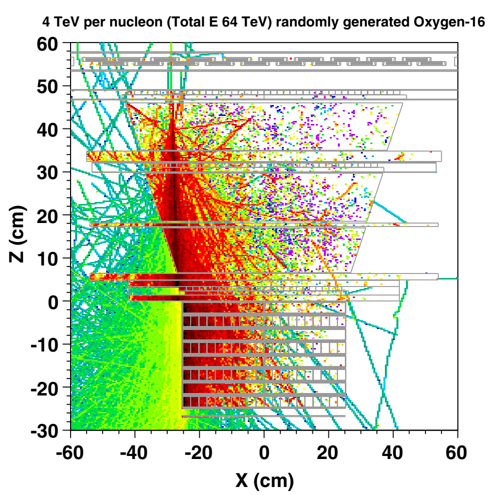

Fig. 11. A 64 TeV ^{16}O nucleus interacting in the ATIC detector. Colors in the plot denote different densities of energy deposit in the detector. The order of colors from maximum to minimum density are black, red, orange, yellow, green, blue and purple. (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

8. Event generation and reconstruction

An important goal of the simulation for the ATIC detector is to calculate efficiencies for various cuts applied to the data, so that an absolute cosmic ray flux can be obtained. The spectra of cosmic rays is well described by an inverse power law in energy with differential flux given by $\frac{dn}{dE} = CE^{-2.70}$. We have written a user code to generate events according to the above power law with energies ranging from 10 GeV to 100 TeV. The position is randomly chosen to be between −40 cm and +40 cm in both x and y. All events were generated in a plane at 10 cm above the top of the detector. The spectra of generated events is shown in Fig. 12.

We ran the ATIC-FLUKA MC for 1,000,000 protons with energies ranging from 50 GeV to 100 TeV. After applying a fiducial volume cut on the particle trajectory 2.5 cm from the edge of the calorimeter in x and y, 250,000 events remained. Fig. 13 shows the distribution of the energy deposited in the BGO calorimeter for the events passing the fiducial volume cut. The resulting MC generated data are in the same format as the actual data and can be analyzed in the same manner.

To insure the integrity of trajectory reconstruction, we required that every BGO plane satisfy an energy threshold selection of 1.0 GeV. The energy distribution of such events is shown in Fig. 14.

The reconstruction of the trajectory was obtained from a χ^2 fit using the weighted pulse-heights in the BGO crystals. The trajectory was them improved using the position of the hit pixel in the Si-matrix plane as well as any hit scin-

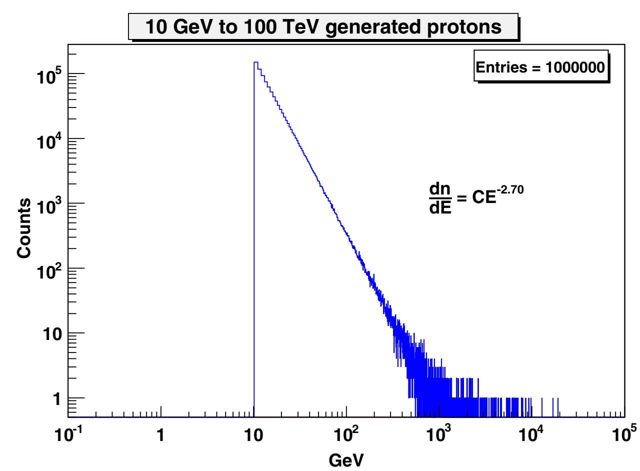

Fig. 12. 10 GeV to 100 TeV randomly generated protons on ATIC using FLUKA.

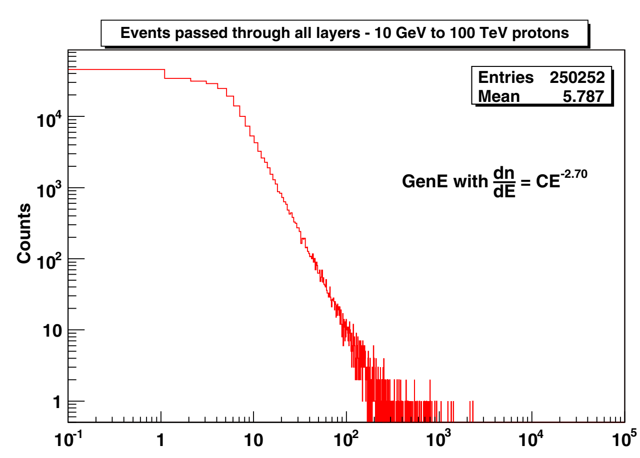

Fig. 13. Energy deposited in the BGO calorimeter by events satisfying the fiducial volume cut.

tillator along its intersection with the hodoscope. To check the goodness of the fit, we extended the trajectory back to the plane where the MC events were generated. The

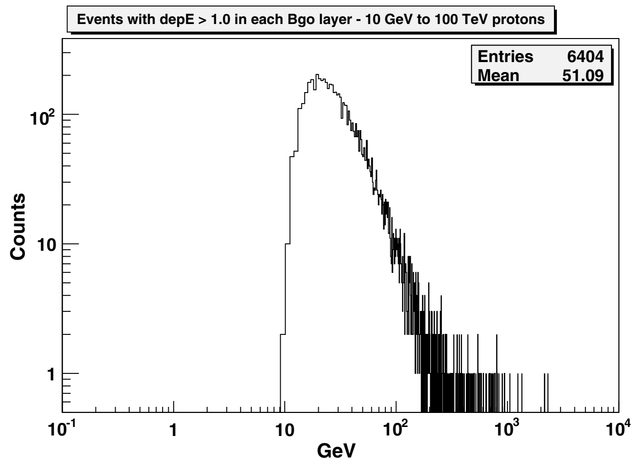

Fig. 14. The energy of the events with a minimum deposited energy of 1.0 GeV in each layer of BGO.

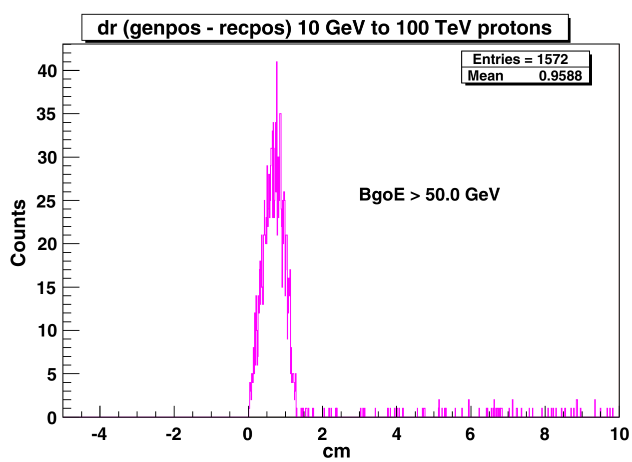

Fig. 15. The distance between the reconstructed positions and the generated positions on a plane 10 cm above the Si-matrix.

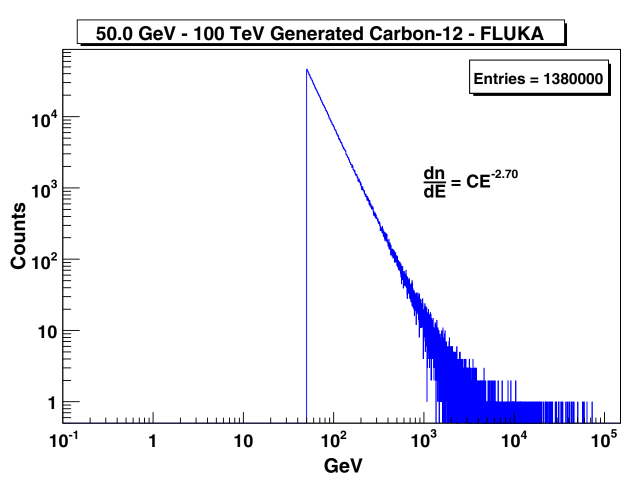

Fig. 16. 50 GeV to 100 TeV randomly generated ^{12}C events.

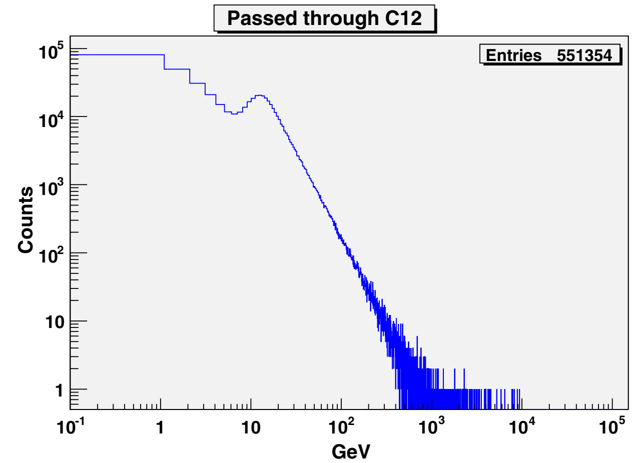

Fig. 17. Energy deposited in the BGO calorimeter by ^{12}C events satisfying the fiducial volume cut.

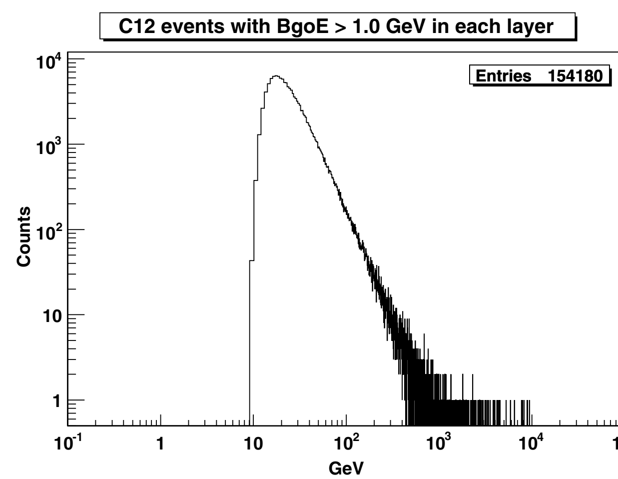

Fig. 18. The energy deposition of ^{12}C events where each layer has more than 1.0 GeV energy deposition.

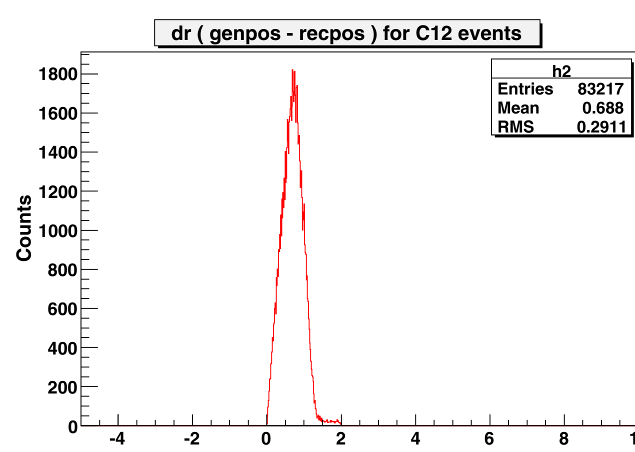

Fig. 19. The distance between the generated position and the reconstructed positions for 50 GeV to 100 TeV randomly generated ^{12}C events.

distance between the generated points and the reconstructed points is shown in Fig. 15.

For the ^{12}C simulation, a total of 550,000 events out of 1,380,000 events passed the above-mentioned fiducial volume cut. Figs. 16–18 show generated, accepted and threshold selected energies, respectively. Fig. 19 shows the distance between reconstructed and generated positions.

9. Conclusion

A simulation code was developed for the ATIC detector using FLUKA-2005. This code can be used to simulate ATIC events for very high energy primary particles (p, e, and μ etc.) and heavy ions. The FLUKA-2005 code provides simulation of particles to the maximum energy ≈100 TeV measured by ATIC. We compared MC data from standard GEANT-3.21 and FLUKA below 20 TeV. The agreement is reasonable. This ATIC-FLUKA MC code provides a pivotal role for the analysis of the ATIC data and will be a part of the analysis package for heavy ions at high energies, not achievable by the GEANT-3.21 MC.

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