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Simulation of 10–100 TeV calorimeter interactions

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Abstract. A Monte Carlo simulation for the interaction of cosmic ray nuclei in an emulsion chamber is described. The simulation uses the `DTUNUC` event generator to handle the high-energy interactions, and `GEANT` to follow lower-energy products.

1 Introduction

A high energy particle interacting with matter will produce an electromagnetic cascade. High energy photons pair produce, the resulting electron and positron bremsstrahlung, and the new photons are once again capable of pair producing. The purely electromagnetic cascade was analyzed analytically by Rossi and Greisen (Rossi, 1941), and Kamata and Nishimura (Kamata, 1958).

High energy nuclei produce electromagnetic showers as well, but characteristics of these showers are dominated by the details of the initial hardronic interaction. This interaction has strong fluctuations in the relative numbers of π^+, π^-, and π^0 particles produced. Most charged pions will escape a thin calorimeter, meaning that the electromagnetic shower is primarily the result of the prompt decay of neutral pions into photons. The variation in pion distribution becomes a variation in the energy manifest in the shower. Understanding the transition curves and k_γ distributions is an important to calibrating any calorimeter-based cosmic ray experiment.

Two interesting features of an electromagnetic cascade are its transition curve and its k_γ value. The transition curve characterizes the rate of a shower's development, generally expressed as the number of electrons as a function of depth. k_γ is the fraction of the incident particle's energy which is ultimately visible in the electromagnetic shower.

`GEANT` is a software tool for simulating the behavior of high-energy particles in matter. Its detailed modeling of physical processes has been validated against accelerator experiments, and it is widely accepted in high-energy physics. However, the interaction models which `GEANT` uses are not appropriate for projectiles with energies above about 100 GeV, and `GEANT` does not handle arbitrary nuclei as projectiles. JACEE studies cosmic ray nuclei in the 10–100 TeV range, so we cannot use `GEANT` alone.

Instead the simulation is divided into two stages. The first stage handles the high-energy components of the simulation. New particles produced in the first stage are routed to a `GEANT`-based second stage if their energy and other attributes are appropriate, and retained in the first stage otherwise.

2 Method

A Monte Carlo simulation, `EMCH` acts as the glue binding the `DTUNUC` (Roesler, 1998) event generator to `GEANT` (CERN Application Software Group, 1993). The highest energy parts of the cascade are handled by `EMCH` and `DTUNUC`, and lower-energy products are routed to `GEANT`. Since it has a very limited scope, `EMCH` is quite simple compared to a general purpose Monte Carlo.

While it is possible to integrate new event generators directly into `GEANT`, it is typically difficult to merge independently written sets of code. Instead `EMCH` allows `DTUNUC` and `GEANT` to exist as completely independent programs, and manages the necessary communication between the two through files. While it may seem that this would be a very slow way for the software to work, the vast majority of processing time is spent in either `DTUNUC` or `GEANT`. There is little to be gained by speeding the communication itself.

The responsibilities of `EMCH` are as follow:

1. Transport of high-energy particles
2. Determination of interaction points
3. Modeling of high-energy interaction through `DTUNUC`
4. Routing of products

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5. Modeling of low-energy shower through `GEANT`

2.1 Transport

Transport is the solution of the equation of motion for the particles traveling through the chamber. The only reason for this to be complicated is to model arbitrary detector geometries. A rectangular emulsion chamber has a simple geometry: the material is a function of *z* only, and the boundaries of the chamber are found by straightforward cuts in *x*, *y*, and *z*.

2.2 Interaction Points

To reduce the bookkeeping associated with modeling multiple physical processes, `EMCH` considers only inelastic collisions. The more peripheral interactions will not contribute appreciably to the shower, so it is appropriate to ignore them.

A table of cross-sections has been pre-computed using `DTUNUC` based on projectile (p, He, Li, O, Fe), target (p, C, N, O, Br, Ag, Pb) and energy ($1-10^7$ GeV in the lab frame, 5 logarithmic steps per decade). Cross-sections for other primaries are interpolated logarithmically between these points. Cross-sections depend only weakly on energy, and are taken by looking up the cross-section for the greatest energy less than the projectile's energy.

The interaction point itself is selected using an approach similar to that of `GEANT`. At the beginning of a particle's travel, the number of interaction lengths it will travel is chosen according to the distribution $N_\lambda = -\ln(\eta)$, where η is a random number uniformly distributed on the interval [0, 1). As the particle travels through each medium N_λ is decremented until zero or until the particle exits the chamber.

When N_λ reaches zero an inelastic interaction takes place. In composite media the target nucleus is chosen according to a distribution weighted by the mass-fractions and cross-sections of each nucleus in the medium.

2.3 High-Energy Event Generator

`DTUNUC` **couple sentences of background on dtunuc**. Version 2.3 (14 Feb 2000) was used for the results described here.

`EMCH` writes a "control-card" for `DTUNUC`, a file which specifies the input parameters to the event generator, and then invokes `DTUNUC`. `DTUNUC` writes each produced particle out to another temporary file.

Table 1 shows the distribution of energy among different particle types for two interactions. Electromagnetic particles can be sent directly to `GEANT`for further simulation, strange particles are dropped, and nuclei will be treated subject to the routing decisions described next.

Product	Energy Fraction	
	0.1 TeV p+Pb	5 TeV C+Pb
p/n	0.22	0.29
heavy	0.16	0.20
$\pi^\pm$	0.10	0.17
π^0	0.058	0.11
γ	0.008	0.013
target	0.38	0.093
strange	0.062	0.11

Table 1. Fraction of total energy represented by different interaction products as simulated by `DTUNUC`. "Heavy" includes fast nuclei with Z ¿ 1, "target" includes slow fragments of the target nucleus, and "strage" includes strange particles and others which cannot be modeled by `GEANT`. Results averaged over 1000 interactions.

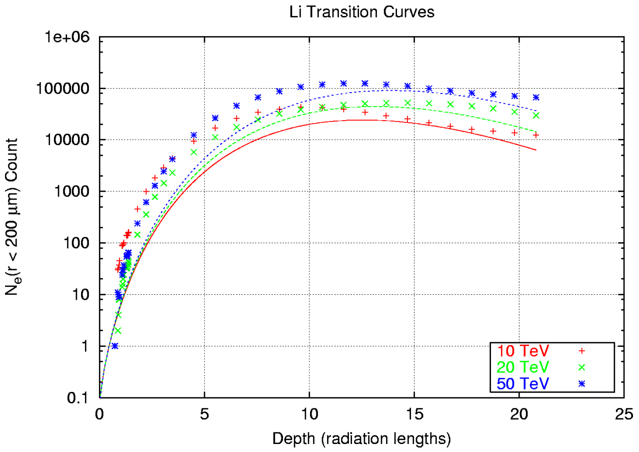

Fig. 1. Number of electrons within 200 microns of the shower axis for 10, 20, and 50 TeV per nucleon lithium interactions.

2.4 Routing

A particle may be routed to one of three places: `GEANT`, retained by `EMCH`, or dropped. Particles are routed according to the following set of rules. If the particle is a nucleus (it is a collection of nucleons), the algorithm starts from rule 1, otherwise it starts from rule 3.

1. If the energy is below 1.5 GeV per nucleon the particle is dropped because it will not contribute appreciably to the shower.

2. If the energy is above 180 GeV per nucleon or atomic mass is greater than 4 AMU, `GEANT` will not be able to handle its interaction, so the particle is retained by `EMCH`.

3. If the particle is a type known to `GEANT` (generally a nucleus with atomic mass less than or equal to 4 AMU, or any other non-strange particle) it will be routed to `GEANT`. Information about the particle is written to a file, to be read later by `GEANT`.

4. If the particle matches none of the above rules, it is dropped.

`EMCH` operates recursively to follow particles routed back to it in step 2.

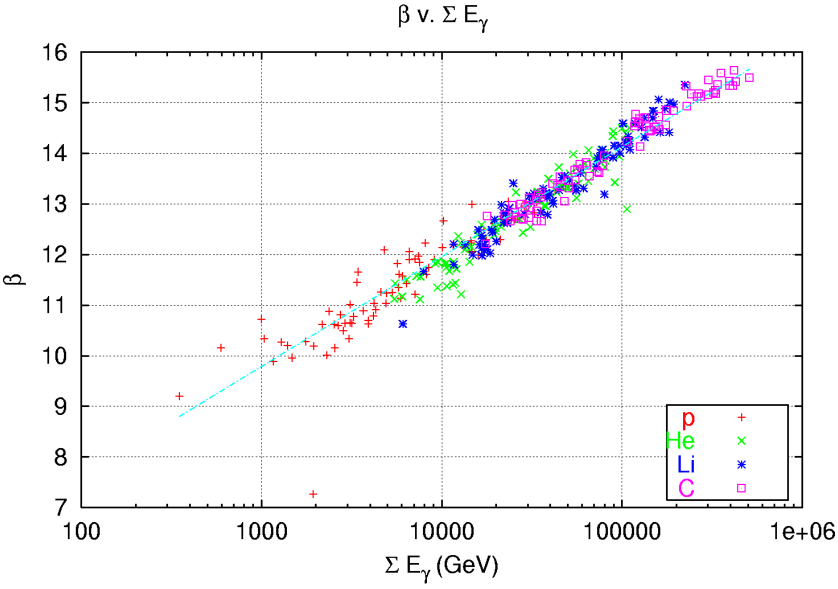

Fig. 2. Relation between the β fit parameter and ΣE_γ for a range of primaries and incident energies.

2.5 Low-Energy Monte Carlo

`EMCH` uses `GEANT` 3.21 to simulate the remainder of the shower. The output of `EMCH` is a file containing a list of vertices and a list of particles. Each vertex is a three-dimensional coordinate where an interaction took place in `EMCH`. Each particle is defined by its vertex, particle id, and momentum. The association of particle with a vertex defines its position. The particle id defines the type of physical particles, using `GEANT`'s mapping of particles to integers. This arrangement of information is convenient for initializing `GEANT`'s part of the simulation.

Following `EMCH`, the shower axis and detector are both aligned along the z-axis. To model an inclined primary arriving with slope m, the detector is scaled in the z direction by $\sec(\arctan(m))$.

The `GEANT` part of the simulation has two major modes, one suitable for computing transition curves, the other for $f(k_\gamma)$ distributions. In the first mode all particles are followed as is normal for `GEANT`. Since the shower is made up primarily of low-energy electrons and photons, the vast majority of simulation time is spent following these particles, but the payoff is detailed transition curves. In the second mode whenever a new photon is produced its energy is added to a ΣE_γ accumulator, but is not followed. This short-circuits the electromagnetic cascade which would result, greatly reducing simulation time and enabling the large number of runs needed for statistically significant $f(k_\gamma)$ distributions. On a 500 MHz Pentium III, the simulation time is approximately 1.5 minutes per TeV per AMU in the first mode, and 0.15 in the second.

Final output, including histograms, is produced from `GEANT`.

3 Results

3.1 Transition Curves

To quantify the transition curve we count the number of electrons produced within 200 microns of the shower axis, as a function of slant depth. The transition curves can be modeled by the form (Roberts, 1989)

$$N_e = \frac{0.31}{\beta^{1/2}} \exp\left[t\left(1 - \frac{3}{2}\ln s\right)\right] \tag{1}$$

where

$$s = \frac{3t}{t + 2\beta}. \tag{2}$$

β is the free parameter which characterizes ΣE_γ, the total amount of energy visible in the electromagnetic part of the shower.

Figure 1 shows simulated transition curves of lithium interactions at three different energies, along with the modeled curves. These are typical of the transition curves we see: the simulation rises faster than the model. Equation 1 models electromagnetic showers initiated by a single photon, while the simulated showers are initiated by the decay of many π^0 to photons, leading to the fast rise.

Figure 2 shows the relation between β and ΣE_γ for a variety of primaries and incident energies. ΣE_γ can be estimated from β as

$$\Sigma E_\gamma = 32.4 \times 10^{\,\beta/2.17} \tag{3}$$

independent of the primary.

3.2 k_γ Distributions

The distribution of k_γ values is dependent on the type of primary nucleus. As can be seen in Figure 3, lighter projectiles

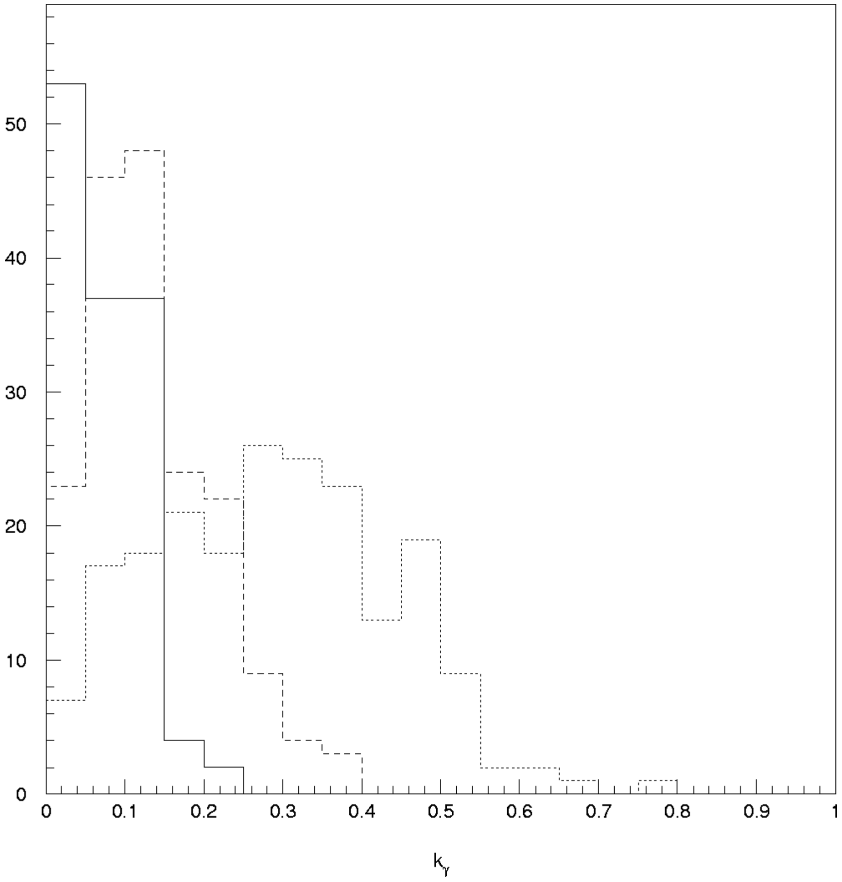

Fig. 3. k_γ distributions for proton, helium, and carbon nuclei interacting with nuclear emulsion in a thin calorimeter. Energy is 10 TeV per nucleon. The proton distribution is the light dashed line; helium, the heavy dashed line; carbon, solid.

lead to a wide distribution of k_γ values, while heavier projectiles have k_γ values which tend to cluster at low end of the range.

Since $k_\gamma \equiv \frac{E_\gamma}{E_0}$ it is important to understand the overall distribution of k_γ in order to estimate the primary energy from our observed ΣE_γ value.

4 Ongoing Work

Continuing work focuses on the nature of the inelastic collision. The electromagnetic shower is affected in part by the range of impact parameters allowed. The relationship between our measured quantities and the degree of inelasticity is under investigation.

Further work will lead to a more detailed understanding of the behavior of TeV hadronic showers, and better energy estimation from calorimeter-based experiments.

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