

## 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.

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### 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 hadronic interaction. This interaction has strong fluctuations in the relative numbers of  $\pi^+$ ,  $\pi^-$ , and  $\pi^0$  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  $k_\gamma$  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  $k_\gamma$  value. The transition curve characterizes the rate of a shower's development, generally expressed as the number of electrons as a function of depth.  $k_\gamma$  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 accelera-

tor 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

## 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  $\eta$  is a random number uniformly distributed on the interval  $[0, 1)$ . As the particle travels through each medium  $N_\lambda$  is decremented until zero or until the particle exits the chamber.

When  $N_\lambda$  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.

### 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

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
$\pi^0$	0.058	0.11
$\gamma$	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  $Z \geq 1$ , "target" includes slow fragments of the target nucleus, and "strange" includes strange particles and others which cannot be modeled by GEANT. Results averaged over 1000 interactions.

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.

### 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  $\Sigma E_\gamma$  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)

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

where

$$s = \frac{3t}{t + 2\beta}. \quad (2)$$

$\beta$  is the free parameter which characterizes  $\Sigma E_\gamma$ , 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  $\pi^0$  to photons, leading to the fast rise.

Figure 2 shows the relation between  $\beta$  and  $\Sigma E_\gamma$  for a variety of primaries and incident energies.  $\Sigma E_\gamma$  can be estimated from  $\beta$  as

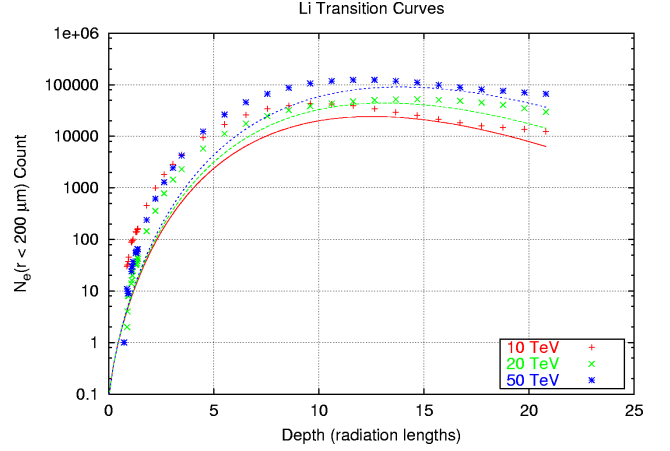
$$\Sigma E_\gamma = 32.4 \times 10^{\beta/2.17} \quad (3)$$

independent of the primary.

#### 3.2 $k_\gamma$ Distributions

The distribution of  $k_\gamma$  values is dependent on the type of primary nucleus. As can be seen in Figure 3, lighter projectiles lead to a wide distribution of  $k_\gamma$  values, while heavier projectiles have  $k_\gamma$  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  $k_\gamma$  in order to estimate the primary energy from our observed  $\Sigma E_\gamma$  value.



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

### 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.

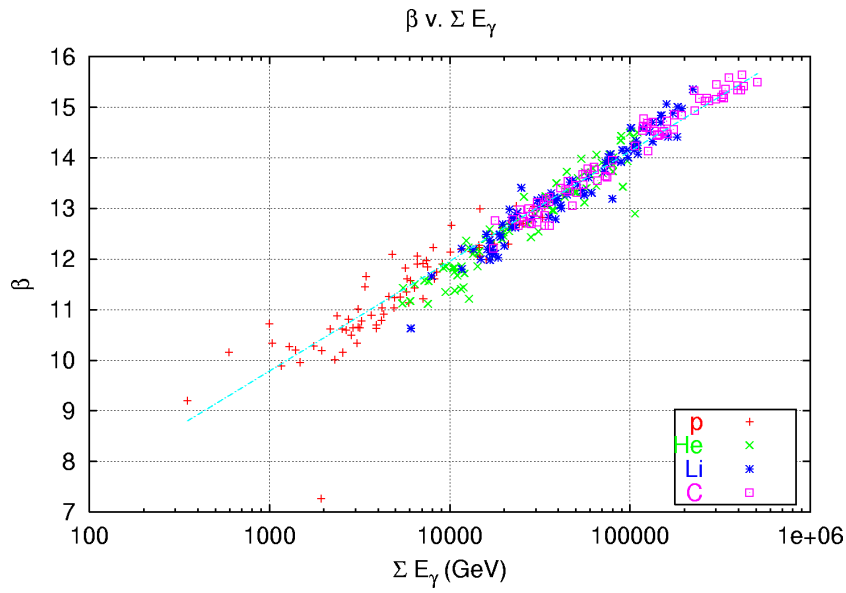
Further work will lead to a more detailed understanding of the behavior of TeV hadronic showers, and better energy estimation from calorimeter-based experiments.

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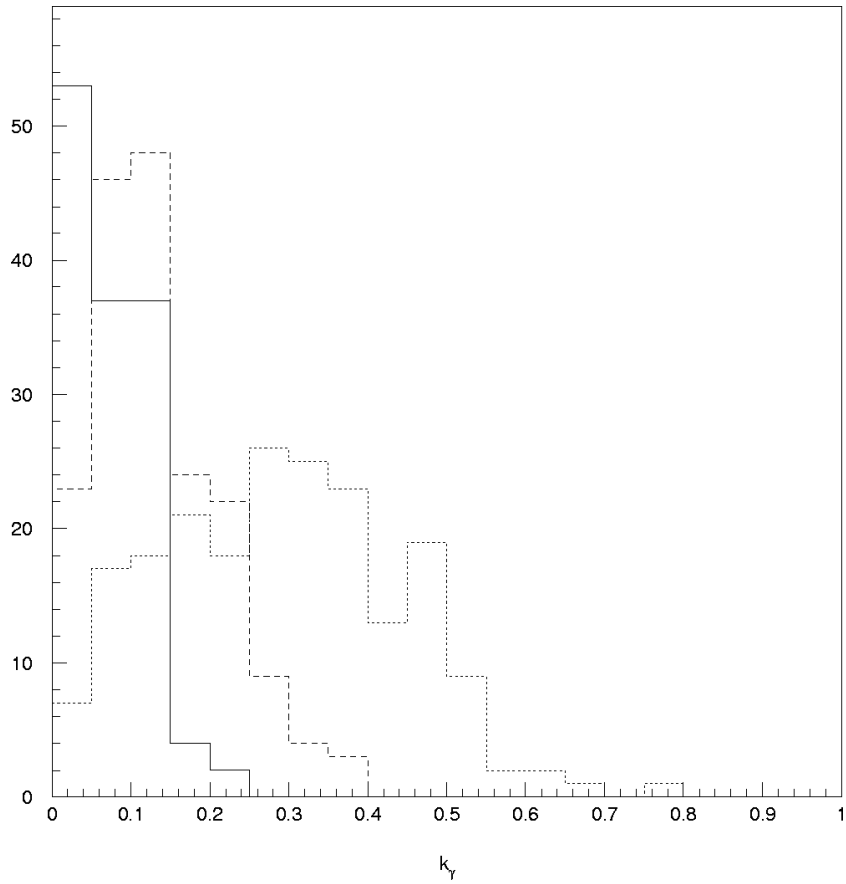
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**Fig. 2.** Relation between the  $\beta$  fit parameter and  $\Sigma E_\gamma$  for a range of primaries and incident energies.



**Fig. 3.**  $k_\gamma$  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.