Proceedings of ICRC 2001: 612 © Copernicus Gesellschaft 2001

ICRC 2001

Detector Responses of the GRAPES III Scintillation and Muon Counters

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Abstract. Detector responses to air shower particles incident on the electron (scintillation) and muon counters of the GRAPES III experiment at Ooty have been investigated using Monte Carlo simulations based on Geant4. The results are summarized as response functions which are then used for simulating air shower events for reducing systematic uncertainty in primary energy estimation. The intensity spectrum of signals detected by the scintillation counter is calculated using these response functions and compared with the observed intensity spectrum.

1 Introduction

The air shower array of the GRAPES III experiment has been in operation at Ooty, India since 1999 with the first-stage configuration of 217 1 m^2 electron (scintillation) counters and 16 560 m^2 muon counters (Ito et al., 1997). The experiment aims to measure the energy spectrum and the chemical composition of cosmic rays around the *knee* region (just above 1 PeV). The dense array of the scintillation counters (8 m span) and the large area muon counters are useful to measure them accurately. Observed results obtained using these detectors have to be exactly compared with results of air shower simulations to estimate above characteristics of cosmic rays as in the recent reports from some experiments (Arqueros et al., 2000; Bernlöhr et al., 2000). In doing such comparisons, it is very important to understand the detector responses to air shower particles correctly. Figure 1 shows the energy spectra of air shower particles at the Ooty level (2200 m asl) generated using the air shower simulation program CORSIKA (Heck et al., 1998), together with the response (energy deposit) functions for one shower particle vertically entering the scintillation counter, which are later explained in detail in this paper. One can see that we have more particles at lower energies down to 1 MeV, but in contrast, the detector response to shower particles rapidly decreases below about 20 MeV. Since the opposite tendencies are competing with each other, estimated shower sizes are fragile with respect to the detector response. One can also see in Figure 1 that the number of secondary gamma rays is an order of magnitude greater than that of electrons especially at low energies. Although our scintillation counters are relatively insensitive to gamma rays because they do not have any converters such as the counters of the Tibet (Amenomori et al., 1990) and HEGRA (Merck et al., 1996) groups, we

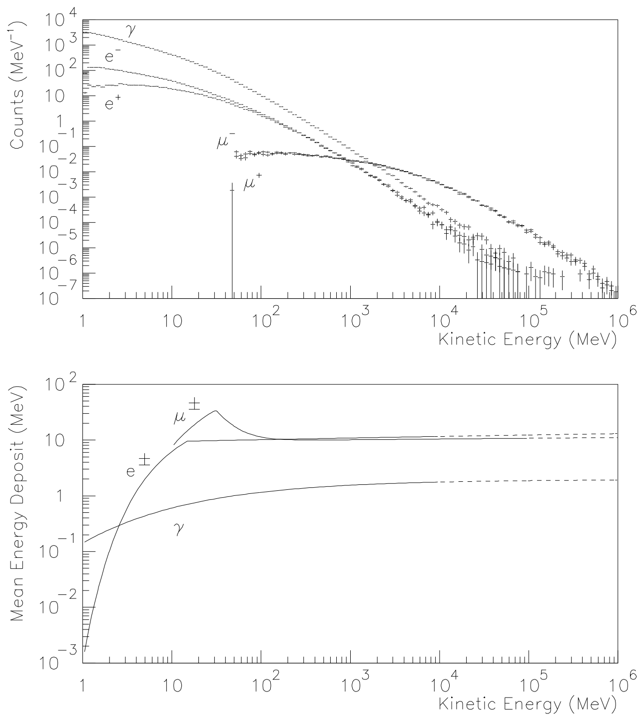

Fig. 1. Energy spectra of air shower particles at the Ooty level generated using the air shower simulation program CORSIKA and the response (energy deposit) functions for one shower particle entering the GRAPES III scintillation counter.

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should investigate how much the contribution of secondary gamma rays is in primary energy estimation.

As for the muon counters, the detector response is closely related to the accuracy of the chemical composition of cosmic rays since mass numbers of primary cosmic rays are probed by detected numbers of secondary muons. Resolution of the mass number estimated from the muon number is not much better than the overall range of observed mass numbers (Weber et al., 1999) owing to the fluctuation of the air shower development. Therefore, the fine structure of the mass number distribution determines the accuracy of the fraction of minor components. The accuracy is also sensitive to the detector response on the same score. Our muon counters can also detect single or multiple muon events without getting any trigger signal from the air shower array, that is, they can be used to monitor the intensity of lower energy cosmic rays and to study the solar modulation of cosmic rays at lower energies (Kawakami et al., 2001). Taking coincidences of 16 muon counters allows us to select primary cosmic rays of different energies and makes a study of the solar modulation possible in a wide energy range using the same detector system. The amplitude of the modulation may be smaller than 0.1% and it is again important to understand the response of the counters correctly.

To reduce systematic errors in estimating primary energies and chemical composition of cosmic rays due to the effects mentioned above, we have investigated detector responses to air shower particles incident on the counters of the GRAPES III experiment, using Monte Carlo simulations based on the detector simulation toolkit Geant4 (Giani et al., 1998). Although the program is still under development, the results currently obtained are summarized in this paper.

2 Simulations and results

2.1 Electron (scintillation) counter

The virtual scintillation counter constructed using Geant4 is visualized and shown in Figure 2. Each of the scintillation counters consists of four 50 cm $\times$ 50 cm $\times$ 5 cm scintillators which are put inside of a container and covered by a rain cover, both of which are made of aluminium of 0.8 mm thickness. The scintillators are viewed by a 2 inch photomultiplier tube (PMT) from the height of 50 cm.

Signals from each PMT are divided and sent to a discriminator and an ADC module. The discriminator has two outputs, one of which is sent to a TDC module and the other is used to generate event triggers. The gain of each scintillation counter is monitored by using penetration of single muons, in which most of muons vertically enter the counter. The ADC value at the single muon peak is calibrated and kept to be about 20 counts. In the configuration of 217 scintillation counters, air shower triggers are generated by using central 96 counters. We have adopted two different trigger conditions, which are called the level-0 and level-1 triggers. The former is a kind of pattern trigger that requires a localized

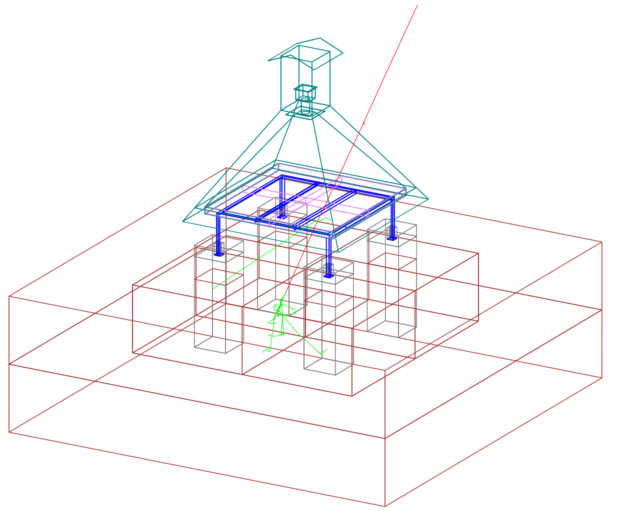

Fig. 2. Virtual scintillation counter of the GRAPES III experiment constructed using Geant4.

pattern of at least three detectors, and the latter requires simultaneous hits of any 9 detectors. The events that satisfy the both conditions are recorded.

5×10^6 events of gamma rays, 2×10^6 events of electrons (and positrons) and 2×10^6 events of muons are generated using the simulation program. Their energies are distributed in the region between 1 MeV and 10 GeV for gamma rays and electrons, between 10 MeV and 100 GeV for muons with the equal weight in the logarithmic scale. The particles are randomly injected into the scintillator area of 1 m $\times$ 1 m from the directions of which zenith angles are smaller than 60°. The simulation program outputs energy deposits in the four scintillators due to incident particles. The obtained energy deposit distribution for each particle is averaged on the incident position and the azimuth angle since it is almost independent of these parameters. The resultant mean energy deposit distributions for gamma rays, electrons and muons are shown in Figure 3. Each of the distributions is fit by a two dimensional function of particle energy and zenith angle ($\cot\theta$) as shown in the figure. The residuals of the fit are well smaller than 10% except for inclined ($\theta \gtrsim 55^\circ$) gamma rays, for which the number of simulated events is not enough. However, the fraction of such inclined events is negligibly small considering the observed zenith angle distribution of primary cosmic rays ($\propto \cos^{7.5}\theta$).

We have tried to reproduce the typical intensity spectrum of signals detected by the scintillation counter, using the mean energy deposit functions defined above. First, 1000 proton showers are generated using CORSIKA with the QGSJET model (Kalmykov and Ostapchenko, 1993) assuming that their energy spectrum has a power-law form of the index of -2.7. Then, shower particles entering each scintillation counter are fed into the functions and resultant energy deposits are accumulated. Here we assume the intensity of scintillation light being independent of the incident position of the particle and

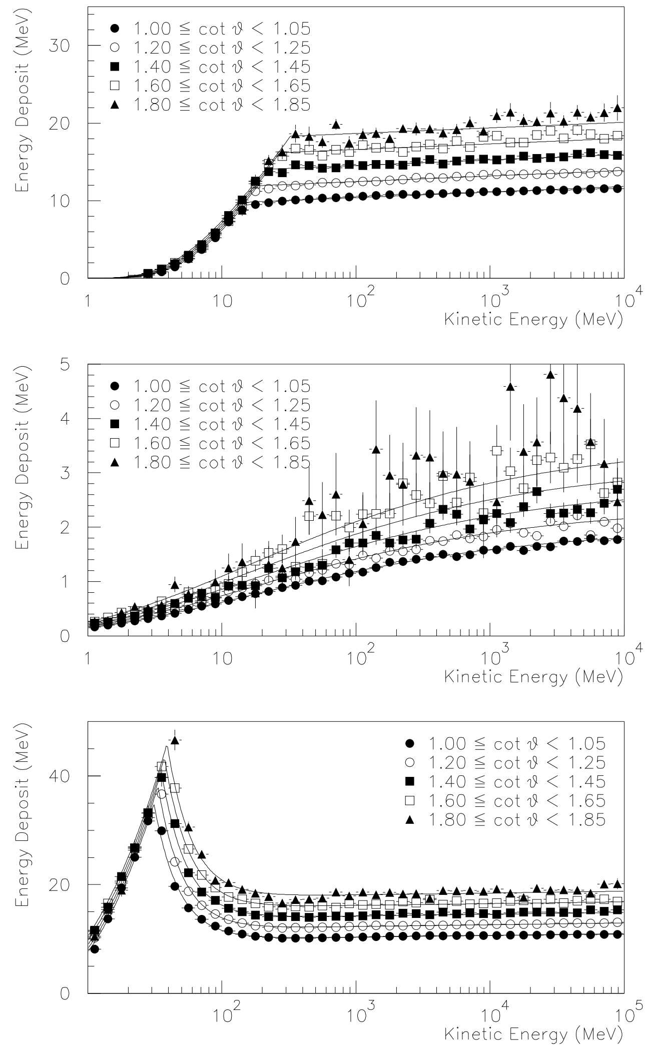

Fig. 3. Mean energy deposit distributions as a function of particle energy for electrons (top), gamma rays (middle) and muons (bottom) obtained using Monte Carlo simulations based on Geant4. Several distributions for different zenith angles ($\cot\theta$) are sampled and plotted.

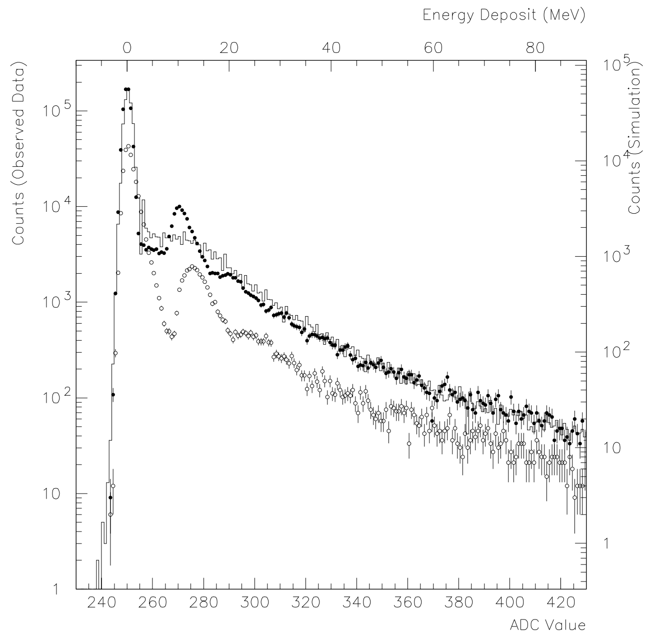

Fig. 4. Intensity spectra of signals detected by the scintillation counter obtained using the full simulation program (filled circle) and the program based on the mean energy deposit functions (open circle), which are compared with the typical observed ADC spectrum (solid line).

ignored the fluctuation of the number of photoelectrons generated in the PMT. The total energy deposit of each detector is compared with the typical discrimination level ($\sim$ 4 MeV) and the hit detectors are compared with the condition of the level-1 trigger. For the sake of comparison, we also fed the same shower particles into the full Monte Carlo simulation program based on Geant4. Figure 4 shows the energy deposit spectra obtained by the above two methods and the typical observed intensity (ADC) spectrum. The spectra are normalized in the horizontal direction using the conversion factor of 2 ADC counts MeV^{-1} assuming the typical energy deposit by a relativistic particle in the scintillator to be 2 $\mathrm{MeV\ g^{-1}\ cm^{2}}$. The fluctuation corresponding to the observed pedestal distribution is added to the simulated spectra. The spectrum of the full Monte Carlo simulation is vertically normalized to the observed spectrum at the pedestal peak.

The overall tendency of the full simulation spectrum agrees with that of the observed spectrum except for the shape near the single particle peak. This difference must come from the fact that we have ignored some fluctuations in the simulations. The spectrum obtained using the energy deposit functions is also similar to the observed spectrum, however, it gives lower triggering rates and a slightly higher value of the single particle peak than the full simulation spectrum. These differences are probably due to the fact that we have also ignored the fluctuation of energy deposits when we define the functions. We should further consider the fluctuations not included in the current simulations.

2.2 Muon counter

The virtual muon counters constructed using Geant4 are visualized and shown in Figure 5. We call this unit of counters ‘muon station’. One muon station consists of four muon counter modules, each of which has four layers of 58 10 cm $\times$ 10 cm $\times$ 6 m proportional counters sandwiched by concrete absorbers of 15 cm thickness and covered by concrete slabs of about 210 cm thickness. The proportional counters are filled by the P-10 gas (Ar 90%, CH_4 10%) of the pressure of 830 mmHg. At each detector module, we are monitoring the rate of any three or four-fold trigger events, which are required to have any three or four coincident layers having at least one hit counter.

2×10^5 muon events have been injected into the virtual muon station. Incident positions are randomly distributed in the area of the counter array and incident directions are also

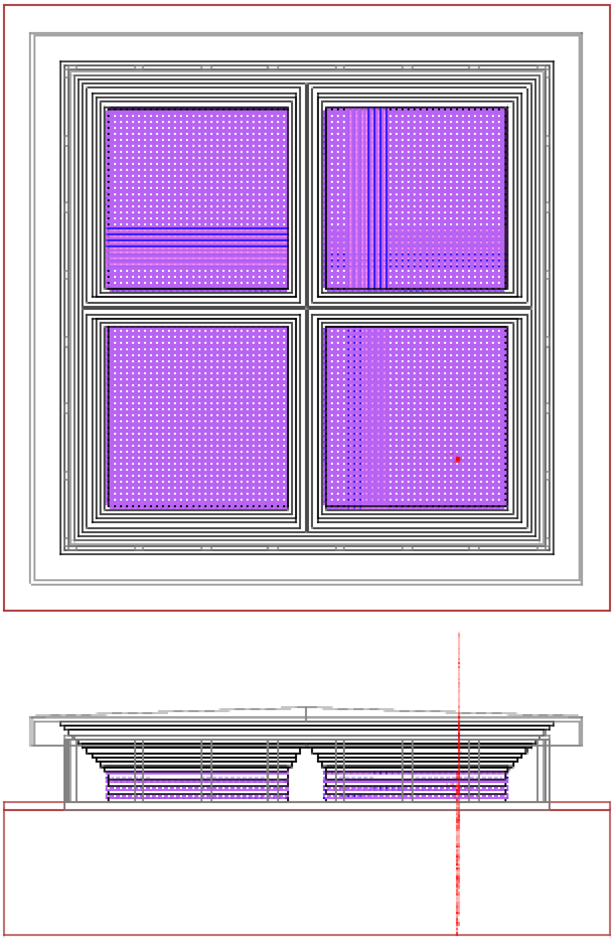

Fig. 5. Top and side views of the virtual muon station of the GRAPES III experiment constructed using Geant4.

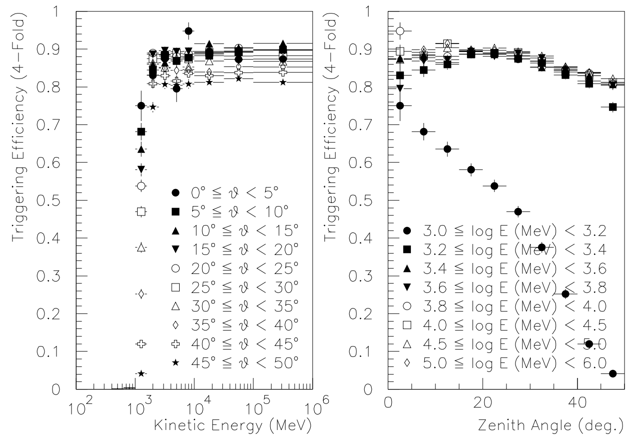

Fig. 6. Triggering efficiencies of four-fold events detected by the virtual muon counter as a function of muon energy and zenith angle.

randomized in the region of $0^\circ < \theta < 50^\circ$. The simulation program outputs energy deposits in the P-10 gas of each proportional counters, which are compared with the typical hit threshold level of 6 keV corresponding to about 0.2 particle and hit counters are compared with the trigger conditions. We have calculated the triggering efficiency that is here defined to be the ratio of the number of triggered events to the number of particles incident on the 6 m $\times$ 6 m area between the second and third layers. The efficiencies are averaged on the incident position and the azimuth angle again as the case of the scintillation counter. Figure 6 shows the four-fold triggering efficiency at one module as a function of energy and zenith angle. One can see that the threshold energy for muons is slightly higher than 1 GeV, which is consistent with the analytical estimation (Ito et al., 1997). The triggering efficiencies slightly decrease with increasing the zenith angle since some inclined particles are out of the geometry of the layers, and have small deficits near the vertical direction in which the probability of muons passing through the gaps between the counters or the counter walls without depositing any energy in the gas is slightly higher.

3 Conclusions

We have constructed the virtual detectors in imitation of the GRAPES III scintillation and muon counters using Geant4 and investigated the responses of them to air shower particles. The intensity spectrum of signals observed by the scintillation counter has been reproduced using the simulation program, but at the moment, the simulated spectra do not agree well with the observed spectrum probably owing to the underestimate of some fluctuations and further investigation is necessary. After some adequate modifications, we are planning to use the simulation program together with the air shower simulation program so that the simulated results reflect exact detector responses.

Acknowledgements. This research was partially supported by a Grant-in-Aid for Scientific Research of the Ministry of Education, Science, Sports and Culture, Japan. We thank the staff members of the Cosmic-Ray Laboratory, TIFR for the installation, operation and maintenance work of the GRAPES III experiment. The help and cooperation of the Radio Astronomy Center, TIFR are gratefully acknowledged for providing site facilities of the experiment.

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