On the Optical Density Spectrum of the PAMIR Emulsion Experiment

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Abstract

The optical density spectrum of electromagnetic particles, measured at the high-altitude emulsion experiment PAMIR, is compared with distributions obtained by Monte Carlo simulations. The extensive air shower simulations are based on the CORSIKA program including different high energy interaction models, like QGSJET, SIBYLL and VENUS. Additionally the Monte Carlo calculations include a detailed simulation of the detector response for the electromagnetic particles based on the GEANT code. This enables to discuss in details the energy resolution and threshold efficiency of the Pamir emulsion calorimeter, as well as comparisons of the interaction models.

1 Introduction:

Direct measurements of the cosmic rays by balloon-borne or satellite experiment provide accurate knowledge of the slopes of the differential primary spectrum up to $\approx 10^{14}$ eV for different nuclei (Wiebel-Sooth, Biermann, and Meyer 1998). The Pamir emulsion experiment ($4370\,$m a.s.l.) could measure the flux of electromagnetic particles in the energy range $4 - 100\,$TeV and of hadrons ($7 - 100\,$TeV) created by interactions of the primaries in the upper atmosphere. The particle flux is estimated by the optical density of the measured spots at the emulsions and the zenith angle of the particles (Bayburina et al. 1983). Detailed Monte-Carlo simulations of both the flux of the particles at high altitudes and the detector effects of the experiment should be helpful to understand the measured distributions. The task of this paper is to compare the measured density distributions of the electromagnetic particles with simulations in the low energy region, where the chemical composition of the primary cosmic rays is known. This additionally gives the possibility to test the air shower simulation program package CORSIKA (Heck et al. 1998) and the different high-energy interaction models included at the energy region around $\approx 10^{14}$ eV especially at the extreme forward direction.

2 Simulations:

For the following consideration 500000 events are generated for three different nuclei (H,He,Fe) and three interaction models (VENUS vers.4.12, QGSJET, SIBYLL vers.1.6), used as generators in the CORSIKA version 5.62 (see Heck et al. 1998). In the case of primary protons the simulations cover the energy spectrum of 10^{13} eV - 10^{16} eV with $dN/dE_0 \propto E_0^{-\gamma}$ ($\gamma_H = 2.75$) and isotropic incidence up to $40°$. In the case of primary Helium (Iron) the used slope is $\gamma_{He} = 2.62$ ($\gamma_{Fe} = 2.60$) in the energy range $2 \cdot 10^{13}$ eV - 10^{16} eV (10^{14} eV - 10^{16} eV). All secondary particles with energies larger than $1\,$TeV at the observation level of the Pamir experiment are taken into account for the further examination. Figure 1 shows the differential energy spectra of the secondary electromagnetic particles at the Pamir level for different primaries and interaction models. The primary flux of the components are normalized to the flux of the primary protons. In general an increasing slope with increasing primary mass is seen, but the role of primary iron nuclei for the total flux of the electromagnetic particles with $E_{e/\gamma} > 1\,$TeV for the Pamir observation level is negligible. The slopes of the spectra are nearly model independent, but the total number of particles is nearly a factor two larger in case of the SIBYLL model than in case of VENUS or QGSJET. In comparison with the experimentally observed slopes there is a good agreement with the simulated ones (Haungs and Kempa 1998).

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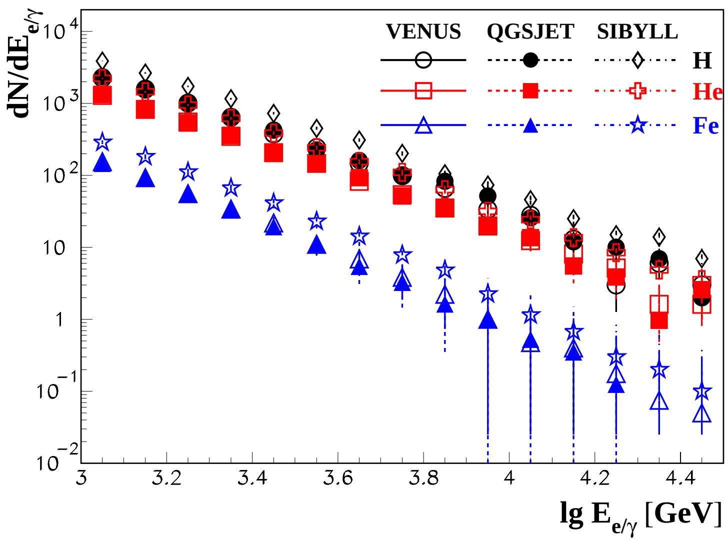

Figure 1: The energy spectra of the simulations for all electromagnetic particles for three different high-energy interaction models. The distributions for primary helium and iron are normalized to the flux of the simulated protons.

For the electromagnetic particles detector simulations are performed based on the GEANT detector simulation tool package. Gamma rays for different fixed energies in the range of 2 to 50 TeV and for four different zenith angles ($0°, 10°, 20°, 30°$) are tracked through the experimental setup. The obtained electron densities at each layer of the X-ray films in bins of $10 \times 10\ \mu\mathrm{m}^2$ are considered for the calculation of the optical densities of the spots at the emulsions in $r < 50\,\mu$m. Fluctuations of the densities at fixed energies and fixed angle-of-incidences are taken into account with high statistical accuracy in the detector simulation (Haungs and Kempa 1997). Following the resulting density distributions for each electromagnetic particle from the EAS simulations with given energy and angle-of-incidence an optical density is calculated by interpolation. Figure 2 shows the average optical density and its variance for all particles as obtained by the CORSIKA simulations.

3 Optical Density Spectrum:

The measured optical density spectrum of single electromagnetic particles for an exposure time $ST = 11.5\,\mathrm{m}^2\mathrm{yr}$ is obtained from the so called working layer (12 c.u.) at the Pamir experiment. The spectrum contains a total number of 1469 electromagnetic particles (Bialobrzeska et al. 1998). Figure 3 shows this optical density distribution compared with simulated distributions, including the detector response described above, the normalization to the exposure time of the measurements, and the well known chemical composition of the primaries in this energy region (Wiebel, Biermann and Meyer 1998). The negligible part of particles coming from primary iron nuclei and the small differences in the slope for different primaries are to be noted.

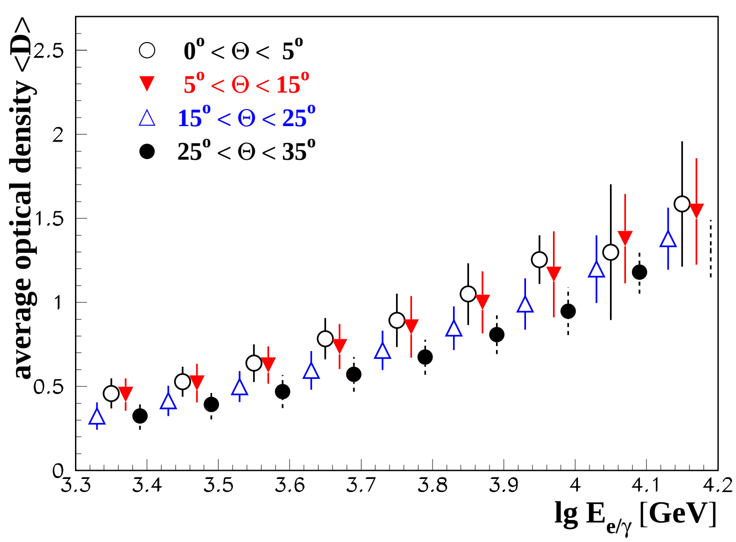

Figure 2: Dependence of the simulated optical density from the particle energy and angle-of-incidence. The error bars represent the variance of the density in each energy range.

Even if there exists a relatively large part of medium primaries (which are not simulated for these considerations), it would not change the distribution and total number of the ”all simulation” distribution of the density spectrum. The relevant primary energy for this particles are between 10^{14} eV and 10^{15} eV. Differences of the two models VENUS and QGSJET are found to be negligible at the comparison of the optical density spectrum. For both models there is an excellent agreement between measurements and simulations. It exists a good agreement in the slope of the spectrum and in the total number of particles, but there are some differences at very small optical densities (low energies). In the simulated distributions particles with a ”true” energy of larger than 3 TeV are taken into account, only. But following the calculations based on GEANT there are some particles with lower energy which can fluctuate to a optical density larger than 0.2 . This would lead to an enhancement of the simulated density spectrum at low values. On the other hand, there exists a ”scanning” efficiency smaller than 100% for the density around the threshold at the experiment, i.e. some single particles are not scanned after the development of the emulsion films. Comparing darkness distributions for different films and years the uncertainty can be evaluated to $\approx 20-30\%$ at the first three data points. The SIBYLL model is unable to reproduce the data. The flux of high energetic electromagnetic particles in forward direction is too large, especially in the well simulated range of darkness $0.5 < D < 1.2$ (Figure 3 lower panel). The differences at high optical densities in all comparisons is due to the limitation of the simulations to high primary energies.

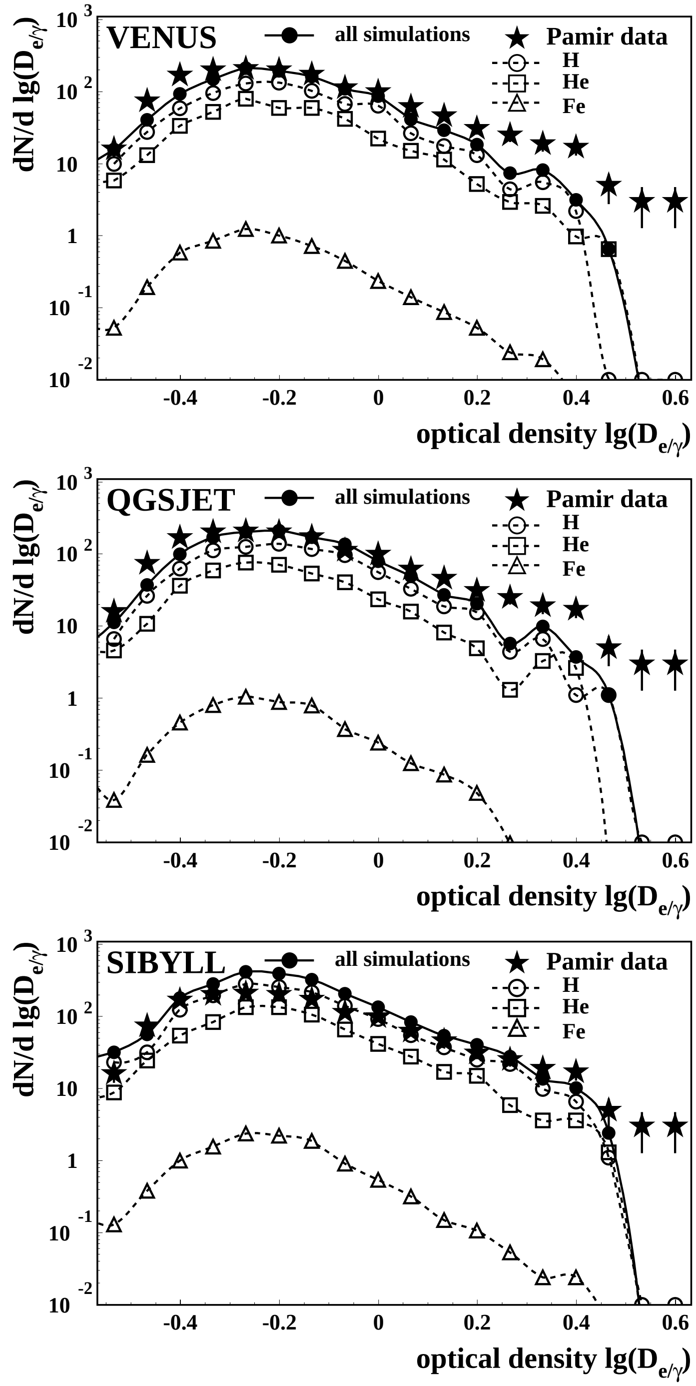

Figure 3: Measured optical density spectrum ($ST = 11.5\,\mathrm{m}^2\mathrm{yr}$) of single particles in the working layer (12 c.u.) of the Pamir experiment ($N_{e,\gamma} = 1469$) compared with the simulated spectra of different primaries normalized to the measured exposure time for three different interaction models.

4 Energy Reconstruction:

After the simulation of the optical density the primary energy of the single particle can be reconstructed using the reconstruction procedures of the Pamir experiment. For each particle the energy is reconstructed from the optical density for the $r = 48\,\mu$m diaphragm according to the functions of Roganova and Ivanenko 1987 including the zenith angle of the particle. Figure 4 shows the quality of the energy reconstruction of this procedure for all particles with an integral optical density larger than 0.2. In spite of the high fluctuations in average the reconstruction quality is quite good and nearly independent of the species of the particle: gamma or electron. At low energies near the threshold the reconstructed energy seems to be larger than the true one. This could be due to systematic effects at the threshold of the Pamir experiment which are not included in the calibration procedure. At energies above 10 TeV a small underestimation of the energy is obvious.

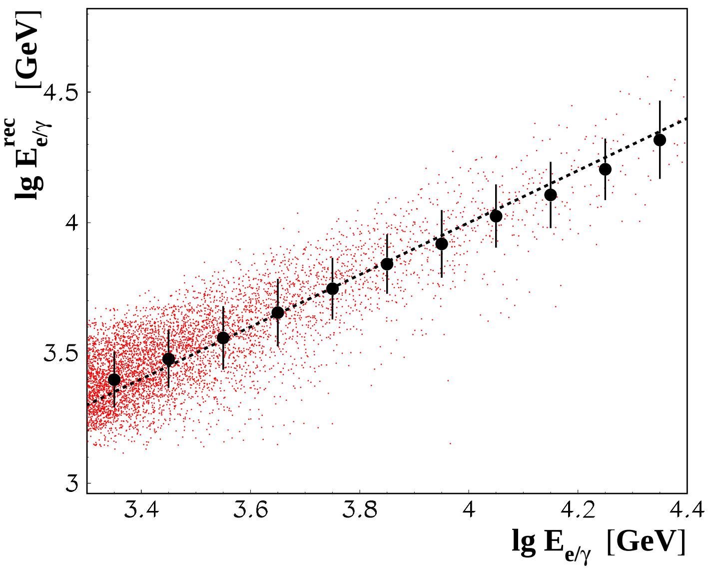

Figure 4: Comparison of the reconstructed energy with the true energy of all electromagnetic particles. Each small dot represents a single particle, the big dots are the reconstructed mean energy with its variance for each bin. For guiding the eyes, a line for $E^{rec} = E^{true}$ is printed.

5 Conclusions:

The quality of the interpretation of cosmic ray experiments at high altitudes is improved by the combination of the air shower simulation in the atmosphere (by CORSIKA with different high-energy interaction models) and the simulation of the detector response (by GEANT). Especially a proof of the energy reconstruction in the Pamir experiment is now possible. It shows a good reconstruction quality, in particular in the ”medium” energy range, but with unexpectedly large fluctuations in the optical density for fixed energies. The good agreement between the measured and the simulated density spectrum shown in this study is an additional hint for a reasonable extrapolation of the interaction models to the extreme forward direction at low energies ($E \approx 10^{13} - 10^{15}$ eV), at least for the QGSJET and VENUS model, whereas the SIBYLL model (version 1.6) is unable to reproduce the data.

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