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Muon production heights determined in the KASCADE experiment

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Muon production heights in EAS provide a specific tool to investigate the longitudinal development of EAS, since muons are little affected by subsequent interactions in the atmosphere. Multiplicity of muons presents also a unique tool to investigate hadronic interaction models. The capability of the Muon Tracking Detector to measure radial and tangential angles of muon tracks in EAS, in combination with the shower direction determined by the Array of the KASCADE experiment, has been investigated. Due to different characteristics in shower development of light and heavy primary cosmic ray particles the radial angle and therefore the related production height is sensitive to the mass of them. Muon production height (MPH) and muon production depth (MPD) were studied in different bins of the muon shower size for measured data and MC simulations, which have been performed using the Monte Carlo program CORSIKA with the hadronic interaction models QGSJet and NEXUS. First composition studies on the basis of MPD distributions have been carried out.

1. The Muon Tracking Detector

The Muon Tracking Detector (MTD) (Fig. 1) [1] is located within the KASCADE experiment [2] in a tunnel beneath a shielding of 18 r.l., giving a 0.8 GeV energy threshold for muons. 16 telescopes equipped with streamer tubes and influence strips are arranged in two rows. For this analysis the three horizontally arranged detector modules of each telescope with a vertical spacing of 82cm have been used.

2. Radial and tangential angles

Due to transverse momentum of the pion in EAS, causing displacement of the muon from the shower axis, and multiple scattering in the atmosphere, muons form an angle in space with the shower axis. To describe the orientation of muon tracks with respect to the shower axis, radial and tangential angles are used (Fig. 2).

The radial angle is defined as angle between direction of the shower axis and the perpendicular projection of the muon track on the radial plane. The radial plane is subtended by the shower axis and the direction between shower core and the position, where the muon crosses the detection plane. The tangential plane is perpendicular to the radial plane, goes through the position of the muon and is parallel to the shower axis. The per-

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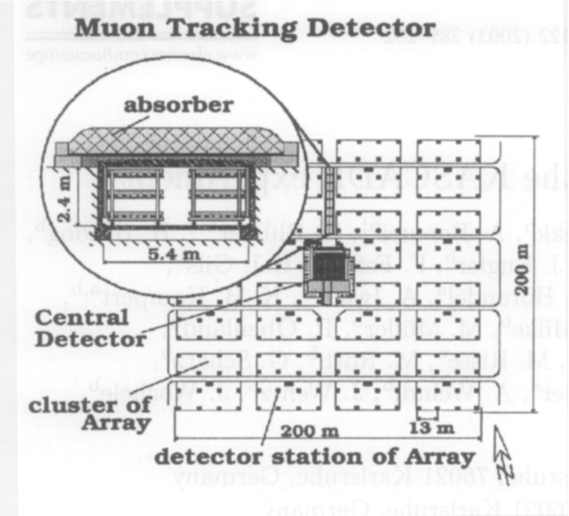

Figure 1. The Muon Tracking Detector (MTD) located in the KASCADE experiment.

pendicular projection of the muon track on the tangential plane defines the tangential angle.
The tangential angle provides a measure of the transverse displacement of the muon direction with respect to the shower axis. Muons produced higher in the atmosphere may exhibit a smaller transverse displacement than those produced deeper, because of larger longitudinal momenta of the parents after the first interaction with air nuclei. The tangential angle distribution is symmetric around zero and exhibits a two component distribution which can be well fitted by two Gaussians. The narrow component is attributed to the combined effect of MTD and Array angle resolution, the broad component mostly to tracks that are produced by muons of low energy close to the MTD energy threshold and by chance (*unwanted*). CORSIKA [3] simulations allow to derive the contribution from multiple scattering in the atmosphere for muons. It typically amounts to 0.5°-0.3° for muon energies between 1-10GeV.
For large values of $\lg(N_\mu^{tr})$ around 5 the narrow σ approaches 0.3°. N_μ^{tr} corresponds to the total number of muons that are within 40-200m at the KASCADE experiment. To reduce the influence

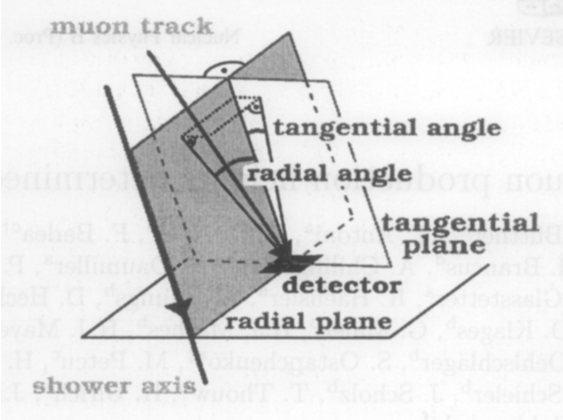

Figure 2. Definition of radial and tangential angles.

of *unwanted* muons the tangential angle was limited to ±0.7° for further analysis.
The distributions of radial angles (Fig. 3) are asymmetric as the radial angle is directly correlated with the MPH. With larger muon number $\lg(N_\mu^{tr})$, i.e. larger energy [4], the average radial angle moves to higher values as the primary particle penetrates deeper in the atmosphere.

3. Analysis

Shower simulations are based on the CORSIKA program in version 5.644 with interaction model QGSJet (version of 1998) and in version 5.948 with NEXUS2 and are followed by simulations of the detector elements of Array and MTD. In the energy range of 10^{14}eV to 10^{17}eV with zenith angles up to 42° about 560000 showers each for proton, carbon, and iron have been simulated in the case of QGSJet and about 360000 showers each in the case of NEXUS. All simulations were done with an $E^{-2.0}$ differential flux spectrum and appropriate event weights (eg. $\propto E^{-0.7}$) were applied to match the recommended flux spectrum [5] in the energy region below the knee; no knee structure was assumed here.
In a first step, distributions of radial angles for measured data and Monte Carlo simulations were

compared. As can be seen in Fig. 3 the corresponding distributions show the expected different behaviour; in average proton induced EAS penetrate deeper in the atmosphere than iron induced EAS at same primary energy. The distributions of radial angles are plotted going to negative values but for calculation of MPH only positive values of radial angles are used. The negative values may be due to muons, that seem to be scattered in the investigated EAS but come from the *opposite* direction. Thus, these muons would cross the shower axis in the radial plane only below detection level. Further analysis should investigate the influence of negative radial angles on MPH distributions also with respect to the finite angle resolution of the MTD-Array system.

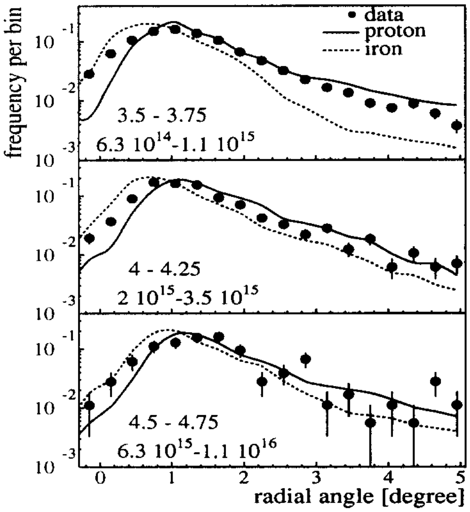

Figure 3. Distributions of radial angles for measured data and simulations of two primaries (QGSJet). $\lg(N_\mu^{tr})$ bins and corresponding energy ranges $E_0[eV]$ of primary particles are indicated.

In Fig. 4 one sees the decreasing of the MPH as $\lg(N_\mu^{tr})$ increases. The mean height of the measured data can be described by the three simulated samples of p, C and Fe of primary cosmic rays for both QGSJet and NEXUS.

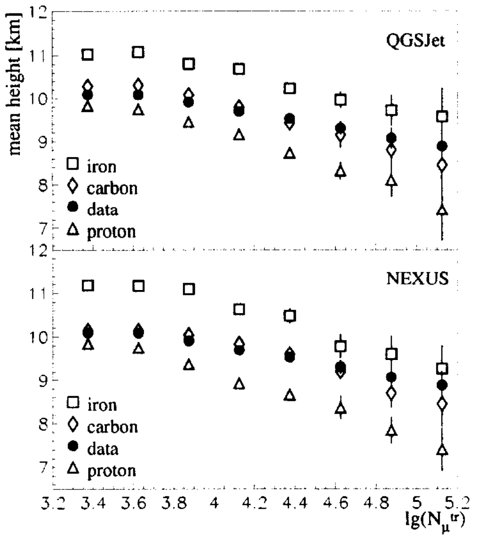

Figure 4. Mean production height for measured data and simulations of three primaries.

The MPD is calculated more accurately by triangulation and taking into account the displacement (tangential angle) of the muons. In Fig. 5 the mean atmospheric depth - calculated by using the MPH and the values of the US-standard-atmosphere [3]- in dependence of $lg(N_\mu^{tr})$ is shown. The behaviour of the measured data can be described by the results of the simulated data. The mean atmospheric depth for muons can be compared with the mean atmospheric depth deduced from Čerenkov [6] and fluorescence light [7] which is assumed to represent the depth of the maximum shower development. Those experiments seem to reveal a deeper maximum shower development than the findings with the MTD.

4. Preliminary studies of primary cosmic ray composition

To derive a composition of the primary cosmic rays in the energy range of $6 \cdot 10^{14} - 6 \cdot 10^{16}$eV by use of MPD, the MPD distributions of simulated data of p and Fe primaries are weighted in such a way that their superposition describes the

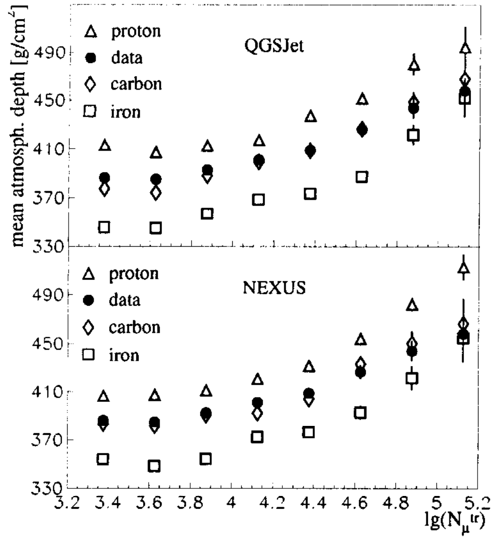

Figure 5. Mean atmospheric depth for measured data and three primaries.

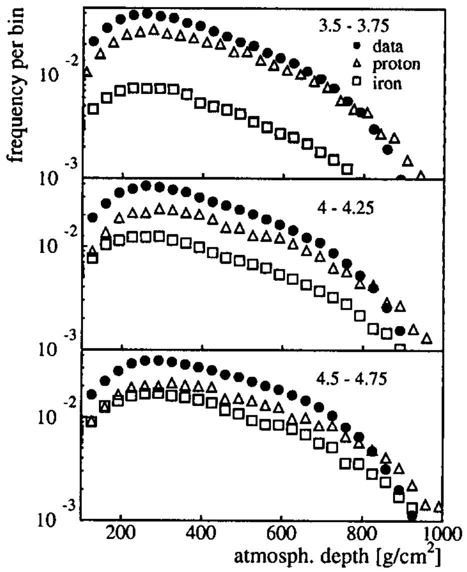

Figure 6. Distributions of MPD for three $\lg(N_\mu^{tr})$ bins.

distribution of the measured data best (Fig. 6). The percentage of the relative contributions of p and Fe primaries shows an increase of the Fe component from 20% to about 40% for $\lg(N_\mu^{tr})$ from 3.5 to 5.25. These values compare well to $\langle lnA \rangle$ values determined by nonparametric methods using KASCADE data [8].

5. Discussions and outlook

It has been shown that MPH and MPD are sensitive to the mass of the primary cosmic ray particles. However, one needs a large enough sample of data to give any prediction of the possible composition as fluctuations of individual EAS are effecting the measured quantities (radial angles).

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