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Results from KASCADE–Grande

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ABSTRACT

The KASCADE–Grande experiment, located at Karlsruhe Institute of Technology (Germany) is a multi-component extensive air-shower experiment devoted to the study of cosmic rays and their interactions at primary energies 10^{14}–10^{18} eV. Main goals of the experiment are the measurement of the all-particle energy spectrum and mass composition in the 10^{16}–10^{18} eV range by sampling charged (N_{ch}) and muon (N_{μ}) components of the air shower. The method to derive the energy spectrum and its uncertainties, as well as the implications of the obtained result, is discussed. An overview of the analyses performed by KASCADE–Grande to derive the mass composition of the measured high-energy comic rays is presented as well.

1. Introduction

The study of the energy spectrum and of the chemical composition of cosmic rays are fundamental tools to understand origin, acceleration and propagation of cosmic rays. The energy range between 10^{16} eV and 10^{18} eV is quite important from the astrophysical point of view because it is expected that in this energy range the transition between galactic and extra-galactic origin of cosmic rays will occur. The results obtained at lower energies by KASCADE [1] and EAS-TOP [2] as well as by other experiments suggest that the knee in the primary energy spectrum around 3–4 $\times 10^{15}$ eV is due to the break in the spectra of elements with light mass ($Z<6$). Several models foresee a rigidity dependence of such breaks. Therefore, a knee of the heaviest components would be expected in the range of 10^{16}–10^{18} eV. Various theories with different assumptions try to explain the rather smooth behavior of the cosmic ray energy spectrum in this energy range (i.e. [3,4]). In order to discriminate among the different models, a very precise measurement of the possible structures of the energy spectrum and of the evolution of the composition is needed.

2. The apparatus

The KASCADE–Grande experiment [5] (see Fig. 1) is a multi-detector setup consisting of the KASCADE experiment [6] with the Muon Tracking Detector (MTD) [7], the trigger array Piccolo and the

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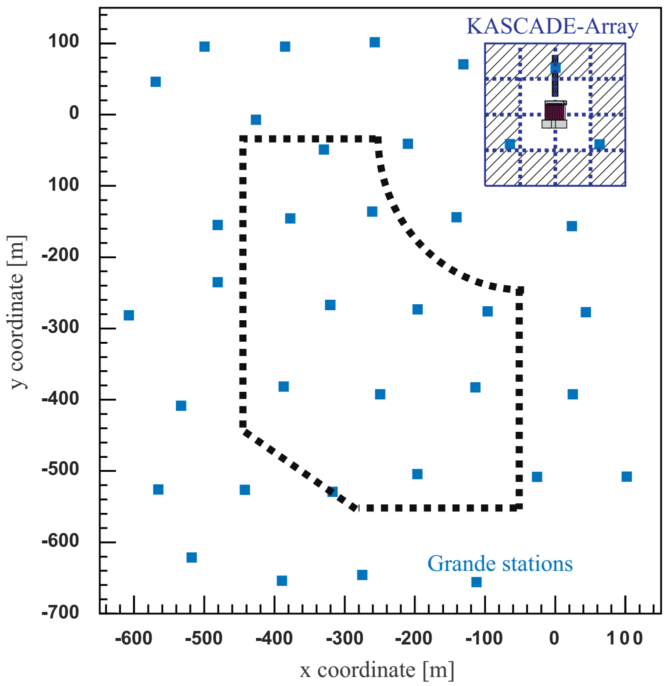

Fig. 1. Layout of the KASCADE–Grande experiment: The original KASCADE and the distribution of the 37 stations of the Grande array are shown. The outer 12 clusters of the KASCADE array employ also shielded μ-detectors. The dashed line shows the area used in the present analysis.

scintillator detector array Grande. Additionally, KASCADE–Grande includes an array of digital read-out antennas, LOPES [8,9], to study the radio emission in air showers at $E > 10^{17}$ eV. Most important for the analyses presented here are the two scintillator arrays: KASCADE and Grande. At the end of the last section some results obtained with the MTD are shown. The KASCADE array comprises 252 scintillator detector stations structured in 16 clusters. The detector stations house two separate detectors for the electromagnetic (unshielded liquid scintillators) and muonic components (shielded plastic scintillators) where muon detectors are housed in 12 clusters (or 192 stations), only. This enables to reconstruct the lateral distributions of muons and electrons separately on an event-by-event basis. The Grande array is formed by 37 stations of plastic scintillator detectors, 10 m^2 each (divided into 16 individual scintillators) spread on a 0.5 km^2 surface, with an average grid size of 137 m. Grande is arranged in 18 hexagonal clusters formed by 6 external detectors and a central one. Grande and KASCADE arrays are both triggered when all the 7/7 stations in a hexagon have fired (rate ~ 0.5 Hz). Full efficiency for proton and iron primaries is reached at $\log N_{ch} > 5.8$. For a subsample of events collected by the Grande array it is possible to compare on an event-by-event basis the two independent reconstructions of KASCADE and Grande. By means of such a comparison the Grande reconstruction accuracies are found to be for the shower size: systematic uncertainty $\leq 5\%$, statistical inaccuracy $\leq 15\%$; for arrival direction: $\sigma \approx 0.8^\circ$; for the core position: $\sigma \approx 6$ m [5]. All of them are in good accordance with the resolutions obtained from simulations. The MTD is a large area (128 m^2) streamer tube tracking detector. Its aim is to identify muons ($E_\mu > 0.8$ GeV) and their angular correlation in extensive air showers by track measurements under 18 r.l. shielding with the resolution $\sigma \approx 0.35^\circ$.

3. The analysis

The technique employed to derive the all-particle energy spectrum and its mass composition is based on the correlation between the size of the charged particles (N_{ch}) and muons (N_μ) on an event-by-event basis. The method itself has been described in detail in Ref. [10]. Here, we summarize the main points.

A sample of Monte Carlo data was simulated including the full air shower development in the atmosphere, the response of the detector and its electronics as well as their uncertainties. The parameters reconstructed from simulation are obtained in the same way as for real data. The EAS events were generated with an isotropic distribution with spectral index $\gamma = -3$ and were simulated with CORSIKA [11] and the hadronic Monte Carlo generators FLUKA [12] and QGSJet II-03 [13,14]. Sets of simulated events were produced in the energy range from 10^{15} eV to 10^{18} eV with high statistics and for five elements: H, He, C, Si and Fe, representative for different mass groups ($\approx$353.000 events per primary). Few events up to 3×10^{18} eV were also generated in order to cross-check the reconstruction behavior at the highest energies.

Grande stations [5] are used to provide core position and angle-of-incidence, as well as the total number of charged particles in the shower, by means of a maximum likelihood procedure comparing the measured number of particles with the one expected from a modified NKG lateral distribution function [15] of charged particles in the EAS.

The total number of muons is calculated using the core position determined by the Grande array and the muon densities measured by the KASCADE muon array detectors. The total number of muons N_μ in the shower disk (above the energy threshold of 230 MeV) is derived from a maximum likelihood estimation assuming a lateral distribution function based on the one proposed by Lagutin and Raikin [16]. The reconstruction procedures and obtained accuracies of KASCADE–Grande observables are described in detail in Ref. [5].

For the reconstructed events, we restricted ourselves to events with zenith angles lower than 40°. Additionally, only air showers with cores located in a central area on KASCADE–Grande were selected. With this cut on the fiducial area, border effects are discarded and possible under- and overestimations of the muon number for events close to and far away from the center of the KASCADE array are reduced. All of these cuts were applied also on the Monte Carlo simulations to study their effects and to optimize the cuts. Full efficiency for triggering and reconstruction of air-showers is reached at primary energy of $\approx 10^{16}$ eV, slightly depending on the cuts needed for the reconstruction of the different observables [5].

The analysis presented here is finally based on 1173 days of data and the cuts on the sensitive central area and zenith angle correspond to a total acceptance of $A = 1.976 \times 10^9$ cm^2 sr, and an exposure of $N = 2.003 \times 10^{17}$ cm^2 s sr, respectively.

With Monte Carlo simulations a formula is obtained to calculate the primary energy per individual shower on the basis of N_{ch} and N_μ. The formula takes into account the mass sensitivity in order to minimize the composition dependence in the energy assignment, and at the same time, provides an event-by-event separation between electron-rich and electron-poor candidates. The formula is defined for five different zenith angle intervals ($\theta < 16.7^\circ$, $16.7^\circ \leq \theta < 24.0^\circ$, $24.0^\circ \leq \theta < 29.9^\circ$, $29.9^\circ \leq \theta < 35.1^\circ$, $35.1^\circ \leq \theta < 40.0^\circ$) independently, to take into account the shower attenuation in atmosphere. Data are combined only at the very last stage to obtain a unique power law spectrum and mass composition.

The energy assignment is defined as $E = f(N_{ch}, k)$ (see Eq. (1), where N_{ch} is the size of the charged particle component and the parameter k is defined through the ratio of the sizes of the N_{ch} and muon (N_μ) components: $k = g(N_{ch}, N_\mu)$ (see Eq. (2)). The main aim of the k variable is to take into account the average differences in the N_{ch}/N_μ ratio among different primaries with same N_{ch} and the shower to shower fluctuations for events of the same primary