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Approach to elemental energy spectra of cosmic rays by correlation curves method

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Using correlation information of different observables in extensive air shower experiments allows to reduce the influence on intrinsic fluctuations at the shower development for the reconstruction of energy and mass of the primary cosmic rays. The basic idea is that all showers which are produced by the same initial parameters (energy, mass) have (at least after the shower maximum) similar developments. The method is discussed by applying it to measured KASCADE array data, i.e. by investigating the correlation of the electron and muon numbers of the EAS. The correlation curves are obtained by fitting detailed Monte Carlo simulations including detector response based on different hadronic interaction models. Systematic uncertainties of the reconstruction method are discussed in detail. The resulting energy spectra for individual mass groups of the cosmic rays will be compared for different ranges in zenith angle, for different interaction models and with the results of the KASCADE unfolding procedures [1].

1. Introduction

The observation of the change of the power law slope (the so-called knee [2]) of the all-particle cosmic ray (CR) spectrum at an energy of $\sim 3 \cdot 10^{15}$ eV has induced considerable interest and experimental activities. Nevertheless, despite of about 50 years of extensive air shower (EAS) measurements, the origin of the knee phenomenon has not yet been convincingly explained [3]. Many of the hypotheses explaining the knee, predict a detailed shape of the primary cosmic ray spectrum around the knee, but with specific variations of the elemental composition. Thus the experimental access to attack the knee problem is to perform detailed and accurate measurements and sophisticated reconstruction methods of the energy spectra of individual cosmic ray elements or elemental groups, at least.

In this studies we present a method to reconstruct the energy spectra of CR elemental groups by an investigation

of the correlation of the electron, N_e, and muon, N_μ, numbers in the EAS. The method and some preliminary results are discussed by applying it to measured KASCADE array data.

The KASCADE experiment [4] located at the site of the Forschungszentrum Karlsruhe, Germany, measure various observables of extensive air showers with primary energy between 10^{14} and 10^{17} eV. It consists of three major detector components: the field array, the muon tracking detector and the central detector complex. The field array extends over an area of 40.000 m^2 and consists of 252 detector stations for the detection of the electron and the muon component of the EAS.
The simulation of the EAS development have been performed using the QGSJET [5] and SIBYLL [6] hadronic interaction models embedded in the CORSIKA program set (ver. 6.15)[7]. Low energy hadronic interactions are treated by the FLUKA model [8]. In the case of QGSJET about 2 millions of EAS in the energy interval of 10^{14} eV to 10^{18} eV for each of 5 primaries (p, He, C, Si, Fe) have been simulated. The energy distribution follows a power law with a slope index of -2. The zenith angles are distributed in the range $[0^\circ - 42^\circ]$. Same characteristics are valid for the SIBYLL case, but with lower statistics. In order to take into account the installation response a detailed GEANT [9] simulation of the KASCADE detectors are performed. The shower observables are reconstructed by the standard KASCADE reconstruction software.

2. Method

The sensitivity of most of the EAS methods to reconstruct the mass of primary cosmic ray particles is rather weak due to huge fluctuations of the shower development in the atmosphere. The reconstruction gets even more difficult at the analysis of EAS with different zenith angles, θ, because the overburden varies with $\cos(\theta)$ representing different column densities for different zenith angles.

An approach to this problem can be found by the correlation analysis of few observables measured at the same shower events. In Fig.1-left all showers of the same mass and energy in a wide interval of zenith angles are shown overlayed on the full distribution of all simulated showers. They are concentrated around specific $log(N_e)$ vs. $dN_{e\mu}$ correlation curves, where $dN_{e\mu} = log(N_e) - log(N_\mu)$. Therefore, the large absolute fluctuations in $log(N_e)$ can be transformed to smaller fluctuations (in relation to the correlation curves also shown in the figure). Additionally, in this approach the energy reconstruction using these curves seems to be independent on the zenith angle due to the fact that showers with large and small θ are placed around the same curves.

For mass reconstruction it was found that the $dN_{e\mu}$ vs. N_μ correlation curves are convenient, as all showers of the same mass and zenith angle in a wide interval of primary energy ($10^{15} - 10^{18}$ eV) are placed around these specific correlation curves. In Fig.1-right it is seen that these curves differ for proton and iron showers significantly.

Hence the applied procedure of energy and mass reconstruction is following: By use of the Monte Carlo (MC) data, in narrow bins of zenith angles for each of the 5 primaries the $dN_{e\mu}$ vs. N_μ-distribution is fitted by a polynomial function with θ and A as free parameters. This yields to a function $dN_{e\mu}(N_\mu, A, \theta)$. The mass of a single shower is then determined from the function by varying A and minimizing the difference between the measured $dN_{e\mu}$ and the function $dN_{e\mu}(N_\mu, A, \theta)$ with fixed (measured) θ and N_μ.
For the energy reconstruction the MC data at different fixed energies and masses are used. Here, the $log(N_e)$ vs. $dN_{e\mu}$ - distributions are fitted with a polynomial function taking E_0 and A as free parameters, i.e. this yields to a function $logN_e(dN_{e\mu}, E_0, A)$. The primary energy is then determined from the function by varying E_0 and minimizing the difference between the measured $log(N_e)$ and the function $logN_e(dN_{e\mu}, E_0, A)$ with fixed (measured) $dN_{e\mu}$ and (beforehand reconstructed) mass A.

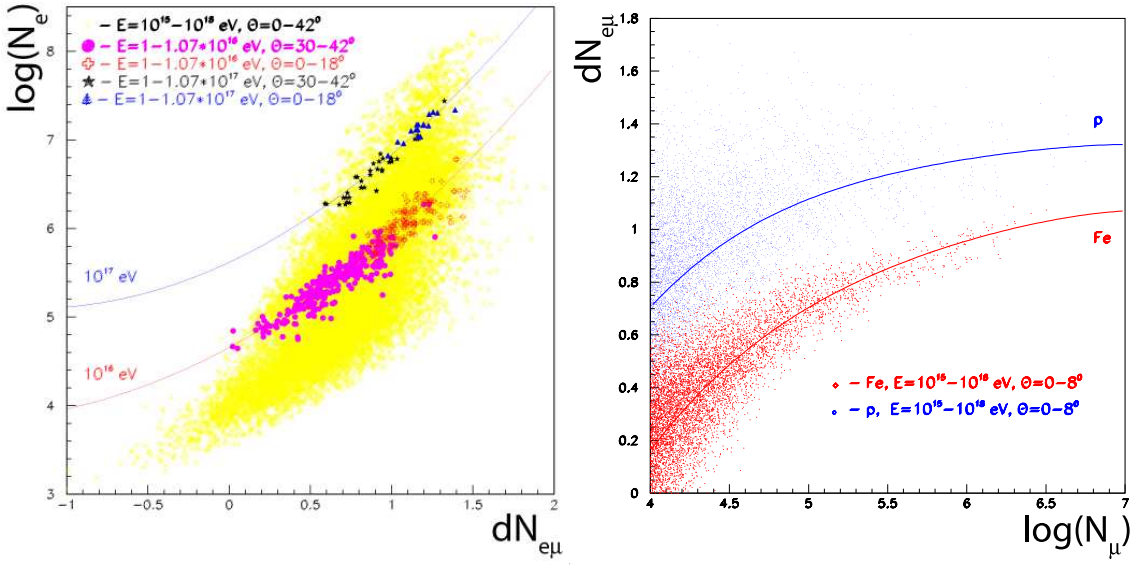

Figure 1. Left:$log(N_e) vs. dN_{e\mu}$-distribution for proton EAS, simulated by QGSJET including the KASCADE detector response, and correlation curves as used for the energy reconstruction. Right:$dN_{e\mu} vs. log(N_\mu)$ dependences for iron and proton showers and correlation curves as used for mass reconstruction.

3. Results

Systematic uncertainties of the method were estimated by applying the described method to artificial elemental spectra obtained by different weightings in slopes and abundances of the Monte Carlo data sets. Resulting energy spectra are then compared to the input-spectra. As example for this procedure Fig. 2 shows input and outcoming spectra for five mass groups. By such investigations it could be shown that the statistical uncertainties of the energy reconstruction is $\sim 15\%$. Systematic uncertainties (inside on hadronic interaction model) are around 2%, only. Uncertainties in the mass classification could be obtained for example concerning the primary Irons as $\sim 27\%$ for Fe-Si classification (Iron misinterpreted as Silicon), $\sim 7\%$ for Fe-C classification, $< 2\%$ for Fe-He classification, and $< 1\%$ for Fe-p classification. Thus, systematical uncertainties of the reconstructed spectra depend mainly on the primary mass composition. These mis-classification probabilities and the systematic uncertainties of the energy estimation necessitates a correction to reconstruct the individual mass spectra, whose procedure is presently in work.

Similar results are obtained using SYBILL generated showers as input spectra. Investigating with same procedures different zenith angular ranges no differences were found in the obtained accuracy, i.e. the reconstruction method is working as expected.

For the application of the method to data a "good run" selection of KASCADE is used. In these runs all clusters and all detectors are present and working and are well calibrated. In total the used sample sums up to about 993 days measuring time. This is the same sample as used in ref. [1], the unfolding analysis of the two-dimensional shower size spectrum.

As preliminary result it was found that the obtained energy spectra (especially for the relative abundances of the different mass groups) depend on the hadronic interaction model used for estimating the correlation curves. Spectra calculated with correlation curves method on the basis of the SIBYLL model lead to differences in the

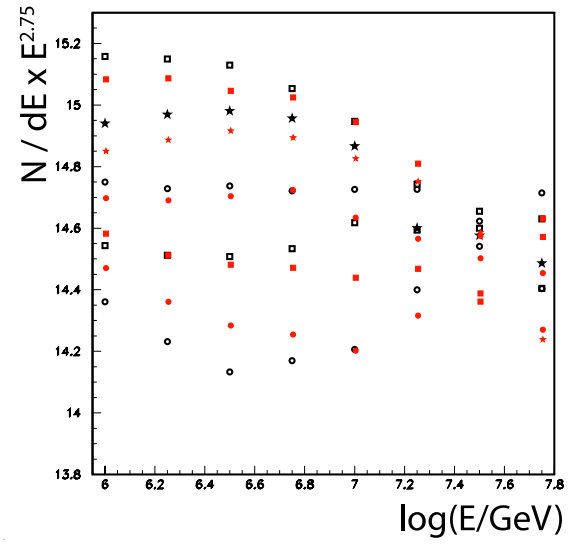

Figure 2. Comparison of simulated elemental mass spectra (p,He,C,Si,Fe from top to down) before (input spectra, open symbols) and after (output spectra, closed symbols) the application of the correlation curve method.

spectra compared to the QGSJET result as it predicts values of N_μ and N_e significantly different for the same primaries.

Nevertheless, the main peculiarities of the reconstructed spectra by SIBYLL and QGSJET models (like the knee in the total and in the light mass groups spectra as well as) as well as the general tendencies of differences between the results of the two models (like the heavier composition in case of SIBYLL) are similar to the results of the unfolding procedures [1].

In addition, due to the much faster procedures in the described method, we could compare resulting spectra of different zenith angle ranges. Indeed, there are differences in the group spectra, but not in the total spectrum if the full sample is divided in subsamples of different zenith angle ranges. If this is also due to inconsistencies in (both) interaction models is still under investigation.

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References

[1] Ulrich H. et al. - KASCADE collaboration, Proc.29th ICRC, Pune (2005), these proceedings
[2] Kulikov G.V., Khristiansen, Soviet Physics JETP 35 (1959) 441.
[3] Haungs A., Rebel H.,Roth M., Rep Prog. Phys. 66 (2003) 1145.
[4] Antoni T. et al. - KASCADE collaboration, Nucl. Inst. Meth. A 513 (2003) 490.
[5] Kalmykov N.N., Ostapchenko S.S., Phys. At. Nucl. 56 (1993) 346.
[6] Engel J. et al., Phys.Rev D50 (1994) 5013
[7] Heck D. et al., FZKA-Report 6019, Forschungszentrum Karlsruhe, 1998.
[8] Fassò A. et al., proc. Monte Carlo 2000, Lisbon, eds. A.Kling et al., Springer (Berlin) 955 (2001)
[9] CERN, GEANT: CERN Program Library Long Writeups, 1993