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Separation of the light and heavy mass groups of $10^{16} - 10^{18}$ eV cosmic rays by studying the ratio muon size to shower size of KASCADE-Grande data

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Abstract. KASCADE-Grande is an air-shower observatory devoted to the study of cosmic rays with energies in the range $10^{16} - 10^{18}$ eV. In KASCADE-Grande, different detector systems allow independent measurements of the number of muons (N_μ) and charged particles (N_{ch}) of air showers, which are the basis for several energy and composition studies of cosmic rays. In this contribution, a composition analysis using the shower size ratio lgN_μ/lgN_{ch}, corrected for attenuation in the atmosphere, is described. Using QGSJET II-based simulations of different primaries, it is shown that an energy independent cut on the shower ratio can be chosen in order to separate the cosmic ray events into light and heavy mass groups. The analysis is applied to the KASCADE-Grande data. The energy spectra derived from the analysis are presented.

1. Introduction

Knee-like structures have been found in the spectrum of the light and medium components of cosmic rays in the energy interval $E = 10^{15} - 10^{17}$ eV [1]. These kinks produce the overall feature in the all-particle cosmic ray spectrum known as the knee, which was discovered by Kulikov and Khristiansen almost 50 years ago [2]. The origin of such a features is subject to several interpretations [3, 4, 5]. Some astrophysical models, where magnetic fields are involved, predict a loss of efficiency at the sources beginning at an energy that scales with the atomic number of the cosmic ray particle, which could cause the observed kinks in the energy spectra of the light and medium components of cosmic rays [4]. The position of the kinks could also be a function of the atomic mass of the nuclei of the cosmic rays [5]. In any case, both kinds of models predict that there should be also a knee-like structure in the energy spectrum of the heavy component of cosmic rays in the interval from 10^{17} to $5 \cdot 10^{17}$ eV. KASCADE-Grande was designed to address the problem of the so-called iron-knee by studying cosmic rays with energy in the interval $E = 10^{17} - 10^{18}$ eV [6]. For this task, measurements of both composition and energy of cosmic rays become imperative. In KASCADE-Grande, that information can be addressed indirectly by using information from both the muon (N_μ) and charged number[1] of particles (N_{ch}) of the extensive air-showers (EAS) at ground level induced by cosmic rays in the atmosphere. In this contribution, the ratio of the muon to charged particle numbers is employed to separate the light and heavy mass composition of cosmic rays, using the dependence of the aforementioned ratio to the type of primary particle. The technique is briefly described and results are presented.

2. The KASCADE-Grande experiment

The cosmic ray detector called KASCADE-Grande comprises several particle detection systems in order to sample the shower front of the EAS at ground level [6]. The instrument is located at the place of the Forschungszentrum Karlsruhe, Germany ($110\,\mathrm{m}\,a.s.l.$). Two arrays are the main components of the experiment. The first one, called Grande, is $700 \times 700\,\mathrm{m}^2$ in size and uses $37 \times 10\,\mathrm{m}^2$ plastic scintillator detectors to estimate N_{ch}, the core and the arrival direction of the EAS. Measurements of N_μ are performed independently with a second array of a smaller area ($200 \times 200\,\mathrm{m}^2$) composed by 252 e/γ and shielded detectors. Estimated systematic uncertainties on N_{ch} and N_μ are less than 5% and 20%, respectively [6].

3. Analysis and results

The analysis was performed on a particular subset of data with zenith angles, θ, below $40°$, with reconstructed cores in a fiducial area of $1.52 \times 10^5\,\mathrm{m}^2$ inside the central region of Grande and with shower sizes $lgN_{ch} > 4.7$ and $lgN_\mu > 4.6$. The cut on the zenith angle was chosen to avoid an increasing zenith angle uncertainty on the particle numbers, while the cut on the area, to reduce the influence of systematic effects from the edges of the Grande array. For these selection criteria, the maximum trigger and reconstruction efficiency is achieved at a threshold energy of $lg(E/\mathrm{GeV}) \gtrsim 7.4$. Data was taken during an effective time of ≈ 3.9 years.

Now, since cosmic rays are studied indirectly in KASCADE-Grande, the interpretation of the observational data must rely on MC simulations. Therefore, data sets with simulated events were created[2]. Both air-shower production and development were simulated using the CORSIKA [7] code and the QGSJET II hadronic interaction model [8]. Meanwhile, the response of the detectors to the passage and the interaction of the shower particles was simulated with a GEANT based program.

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[1] Defined as the sum of electrons and muons in the shower.

[2] Data sets for several primaries: H, He, C, Si and Fe and a mixed composition assumption (where the different primary nuclei are present in equal abundances) were generated. A differential energy spectrum with spectral index $\gamma = -3$ was assumed. Both MC and experimental data were reconstructed with the same algorithm.

The analysis technique is described in detailed in [9, 10]. Here, we will summarize the main steps. The analysis begins by properly correcting the muon number for systematic uncertainties with a correction function based on MC simulations[3]. Then, by using the Constant Intensity Cut method (as employed in [11]), the attenuation curves of N_{ch} and N_μ in the atmosphere are independently obtained to be used later to calculate the equivalent particle numbers at a zenith angle of reference, $\theta_{ref} = 21.5°$, which is selected as the mean value of the zenith angle distribution of the measured data. The usage of the CIC method to obtain the attenuation functions and correct the data allows to take into account the effects of the propagation of the shower in the atmosphere in a model independent way.

Using the values of N_{ch} and N_μ at the reference angle, the ratio $Y^{CIC} = lgN_\mu(\theta_{ref})/lgN_{ch}(\theta_{ref})$ is calculated. The sensitivity of the ratio Y^{CIC} is then investigated for different primaries by using MC simulations, as a function of the primary energy. We found, that the mean Y^{CIC} shower ratio for pure primaries is almost energy independent in the region of maximum efficiency, and its value increases according to the mass of the primary nuclei as seen in the left panel of figure 1. If a cut is applied on the Y^{CIC} ratio at 0.84, it is seen that data can be roughly divided into two different sets: the *electron rich* and *electron poor groups*, with the light elements H and He as representatives for the former group, and the heavy elements Si and Fe, for the latter. The chosen cut is independent not only of the energy but also of θ and the core position. A clean separation of the pure elements can not be obtained by this technique. The proportion of missclassified events for protons and iron nuclei is of the order of $\lesssim 15\%$ in the region of maximum efficiency, and it is constant with the reconstructed energy.

In order to find the energy spectrum of each mass group, an energy value must be assigned to each event. The assignment is done using a formula calibrated with MC simulations, $E = f(N_{ch}, N_\mu)$, which exploits the correlation between the mass of the primary of a given energy E and the charged and muon number of particles in the EAS [12]. The reconstructed energy spectra of the *light* and *heavy* mass groups are shown in the right panel of figure 1. A brief look at the spectrum of the *heavy* component allows to identify the presence of a knee-like structure in this spectrum [9, 10]. Fitting the spectrum with a broken power-law expression, it is found that the structure is the result of a change of the spectrum from $\gamma = -2.72 \pm 0.01$ to $\gamma = -3.19 \pm 0.04$ at around $lg(E/\text{GeV}) \approx 7.84 \pm 0.06$. On the other hand, it is worth pointing out that the *light* component of cosmic rays is still present at energies between 10^{17} and 10^{18} eV, however its relative abundance is smaller than that for the heavy component[9, 10]. The all-particle energy spectrum, composed by the sum of the *electron rich* and *electron poor* spectra is also shown in figure 1. As it can be observed, the all-particle energy spectrum is not smooth in the energy interval analyzed. It shows also a kink, which is a direct consequence of the presence of the knee in the *heavy* component of cosmic rays [9, 10]. A fit on the all-particle energy spectrum with a broken power law, reveals that this new feature arises at an energy $lg(E/\text{GeV}) \approx 7.94 \pm 0.08$ and is less pronounced ($\Delta\gamma = -0.14$) than the previous ($\Delta\gamma = -0.47$) one. All the above results are consistent with those obtained in [9, 10] within their errors.

4. Conclusions

By applying a convenient cut on the ratio between the logarithms of the muon and charged number of particles for EAS detected with KASCADE-Grande, the light and heavy mass components of cosmic rays were extracted in the context of the QGSJET II hadronic interaction model. The corresponding energy spectra of each component were estimated. The energy spectrum for the heavy mass group of cosmic rays derived from observational data shows a

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[3] Assuming mixed composition only. The correction function is a function of the arrival angle, the core position at ground and the number of muon particles of the EAS. They have little dependence on the hadronic interaction model employed (QGSJET II, EPOS 1.99 and SIBYLL 2.1). After correction, the systematics on the muon number are $\lesssim 8\%$ above the energy threshold for maximum efficiency.
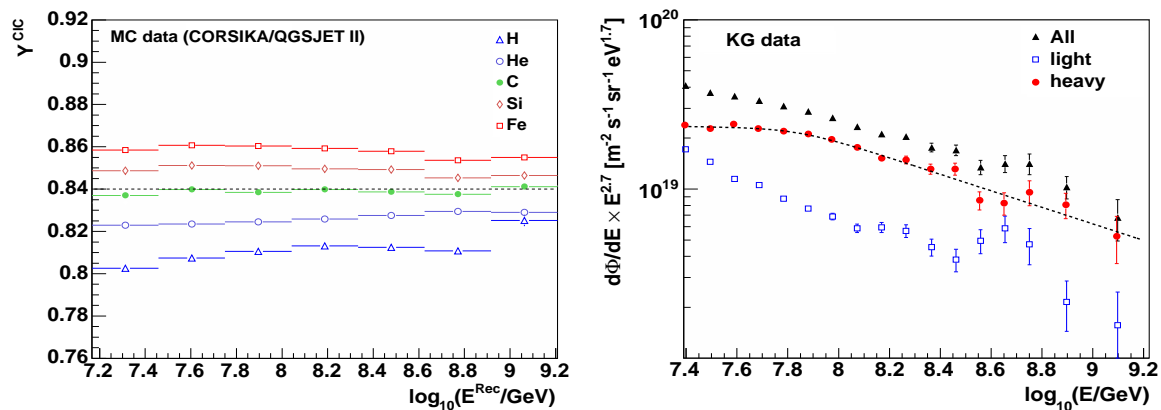
Figure 1. *Left panel*: Estimations of the Y^{CIC} ratio for five primaries (from bottom to top: H, He, C, Si and Fe) shown as a function of the reconstructed energy using MC simulations. The dotted line represents the Y^{CIC} cut used for the analysis. Error bars represent the RMS of the Y^{CIC} distributions. *Right panel*: Energy spectra obtained from the Y^{CIC} analysis (no unfolding technique has been applied). The fit to the spectrum of the heavy component with a broken power-law function is also displayed.

knee-like structure around $E \approx 7 \times 10^{16}$ eV. This component of cosmic rays dominates over the light one at the aforesaid energies and, therefore, the spectral shape of the all-particle energy spectrum around the same energy according to the QGSJET II model.

References

[1] Apel W D et al. 2005 Astrop. Phys. **24** 1
[2] Kulikov G V and Khristiansen G B 1959 Sov. Phys. JETP **35** 441
[3] Hoerandel J R 2004 Astropart. Phys. **21** 241
[4] Peters B 1961 Il Nuo. Cim. **22** 800; Ptuskin V S et al. 1993 Astron. Astrophys. **268** 726; Wick S D, Dermer C D and Atoyan A 2004 Astropart. Phys. **21** 125; Ptuskin V S 2005 AIP Conf. Proc. **745** 14; Binns W R et al. 2008 New Astronomy Reviews **52** 427
[5] De Rújula A 2005 *Proc. Int. Symp. on Lattice Field Theory (Boston, Massachusetts, 24-29 June 2002) (Nucl. Phys. B: Proc. Suppl. vol 151)* eds Edwards R, Negele J, Richards D (Amsterdam: North-Holland) pp 23-32
[6] Apel W D et al. 2010 NIMA **620** 202
[7] Heck D et al. 1998 *Report FZKA 6019* (Karlsruhe: Forschungszentrum Karlsruhe)
[8] Ostapchenko S S 2006 *Proc. Int. Symp. on Lattice Field Theory (Boston, Massachusetts, 24-29 June 2002) (Nucl. Phys. B: Proc. Suppl. vol 151)* eds Edwards R, Negele J, Richards D (Amsterdam: North-Holland) pp 143-146; Ostapchenko S 2006 Phys. Rev. D **74** 014026
[9] Apel W D et al. 2011 PRL **107** 171104
[10] Arteaga-Velázquez J C et al. 2011 Study of the ratio muon size to shower size as a mass sensitive parameter of KASCADE-Grande astro-ph/1111.5436 p 11
[11] Kang D et al. 2009 Cosmic ray energy spectrum based on shower size measurements of KASCADE-Grande astro-ph/0906.4007 p 7; Arteaga-Velázquez J C et al. 2009 The Energy Spectrum of Primary Cosmic Rays Reconstructed with the KASCADE-Grande Muon Data astro-ph/0906.4007 p 11
[12] Bertaina M et al. 2011 Astrophys. Space Sci. Trans. **7** 229