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Measurement of attenuation lengths of hadrons in air showers with KASCADE

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Abstract: Different methods are applied to derive the attenuation lengths of hadrons in air showers with the KASCADE experiment. A data set of unaccompanied hadrons is used (where only a hadron is registered with a calorimeter) as well as full air showers, where also the number of electrons and muons is registered with a field array. The different attenuation lengths obtained are discussed.

Introduction

The measurement of the attenuation lengths of hadrons in air showers provides a suitable experimental access to the properties of high-energy hadronic interactions.

Main detector for the present analysis is the 16×20 m^2 hadron calorimeter of the KASCADE experiment [1]. An iron sampling calorimeter comprising of nine layers of liquid ionization chambers interspaced with absorbers of lead, iron, and concrete. It measures the energy, as well as point and angle of incidence for hadrons with energies $E_h > 50$ GeV. It has been calibrated at an accelerator beam [2]. In addition, for a part of the analyses discussed here the electromagnetic and muonic ($E_\mu > 0.23$ GeV) shower components are registered with a 200×200 m^2 scintillator array [3].

Different methods are discussed to derive attenuation lengths. The values obtained are not a priori comparable to each other since they are based on different definitions. The first part deals with unaccompanied hadrons, i.e. only one hadron is registered with the calorimeter, followed by an analysis of hadrons in air showers.

Unaccompanied Hadrons

For the following analyses the actual vertical thickness X_0 of the atmosphere above the KASCADE experiment is needed. The average ground pressure during the observation time

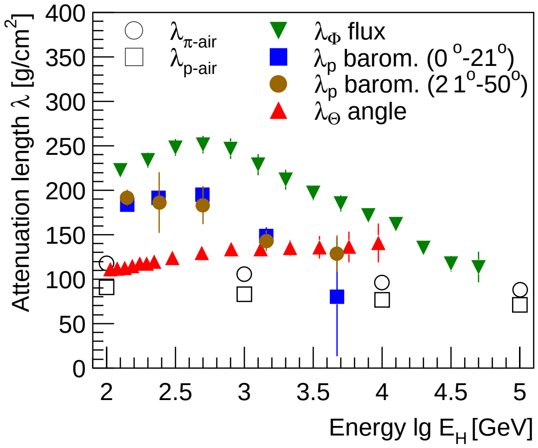

Figure 1: Attenuation lengths derived from the measurement of unaccompanied hadrons applying different methods, see text. For comparison, the open symbols represent the proton-air and pion-air interaction lengths according to QGSJET 01.

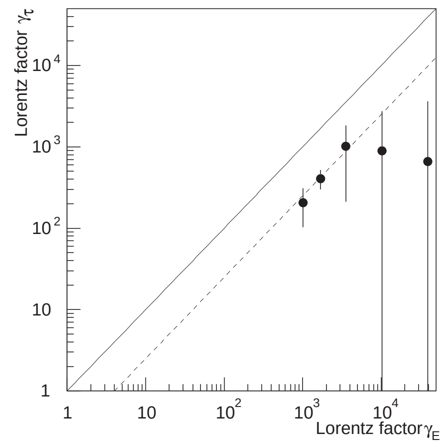

Figure 2: Lorentz factor γ_τ versus γ_E, see text. The solid line corresponds to $\gamma_\tau = \gamma_E$ and the dashed one to $\gamma_\tau = \gamma_E/4$.

amounts to 1004 hPa, corresponding to an average X_0=1023 g/cm^2.

The first method relates the flux observed above the atmosphere to unaccompanied hadrons measured at ground level. Simulations show, that unaccompanied hadrons mostly originate from primary protons [4]. Therefore, the flux of primary protons Φ_0 as measured above the atmosphere by satellite and balloon experiments [5] and the flux of unaccompanied hadrons Φ_H as measured by KASCADE [4] are used and an attenuation length λ_Φ is derived applying $\Phi_H = \Phi_0 \exp(-X_0/\lambda_\Phi)$. The values obtained range from ≈ 250 g/cm^2 at low energies to values around 100 g/cm^2 and are presented in Fig. 1 as function of hadron energy.

The following methods use the change of the measured hadron rate caused by variations of the absorber thickness. One possibility is to investigate the hadron rate as function of the zenith angle Θ of the hadrons, which implies a change in the absorber thickness $X = X_0/\cos(\Theta)$. This yields an attenuation length λ_Θ with $\Phi_H(\Theta) \propto \exp(-X/\lambda_\Theta)$. Fits to the measured data for different energy intervals yield values for λ_Θ as shown in Fig. 1. The values increase slightly as function of energy from ≈ 110 g/cm^2 to about 140 g/cm^2.

The last method described uses a change in the absorber thickness caused by variations in the atmospheric ground pressure p. In addition, the measured rate of unaccompanied hadrons depends on the temperature T_{200} of the atmosphere, measured 200 m above KASCADE. The temperature effect is caused by the fact that for a given pressure (or column density) a higher temperature yields a smaller air density and thus more pions decay. Approximating the atmosphere as ideal gas a temperature change relates to a change of the height of an atmospheric layer. Motivated by CORSIKA [6] air shower simulations it is assumed that most pions in air showers are generated at an atmospheric depth of about 150 g/cm^2, corresponding to $H_0 \approx 14$ km. Applying the ideal gas law the production height is approximated as $H(T_{200}) = H_0(1 + 3.4 \cdot 10^{-3}(T_{200} - T_0))$ with $T_0 = 15°$C.

The pressure and temperature dependencies of the observed rates are described by the relations $\Phi_H(p) \propto \exp(-p/\lambda_p)$ and $\Phi_H(T_{200}) \propto \exp(-H/l_0)$, respectively. The values λ_p and l_0 are determined through an iterative procedure in which the rates are normalized to a standard temperature and pressure. The data have been analyzed in two zenith angle intervals of $0° - 21°$ and $21° - 50°$. The results for λ_p are depicted in Fig. 1 as function of energy. The values for the two zenith angle ranges agree well with each other, and show a decrease from values around 190 g/cm^2 at low energies to about 100 g/cm^2 at higher energies.

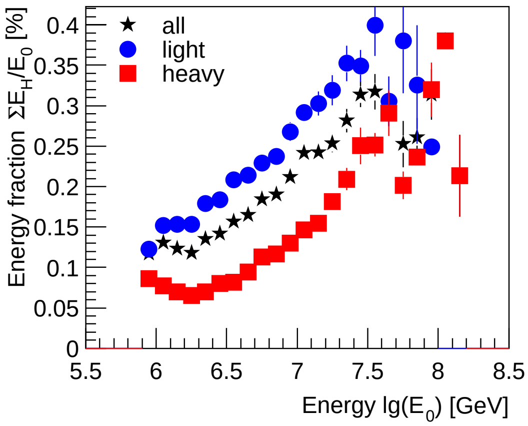

Figure 3: Fraction of energy $\Sigma E_H/E_0$ reaching the ground in form of hadrons as function of estimated primary energy E_0 for all data and for a selection of light and heavy primaries.

As a plausibility check, the temperature dependence has been used to estimate the charged pion life time. l_0 is taken as the decay length of pions, yielding for the life time $\tau = l_0/c$. With the life time of pions in the rest system $\tau_\pi = 2.2 \cdot 10^{-8}$ s the Lorentz factor of the registered hadrons can be estimated $\gamma_\tau = \tau/\tau_\pi$. Since the energy of the hadrons/pions is measured independently with the calorimeter, a second Lorentz factor can be estimated $\gamma_E = E_H/m_\pi$ with the rest mass of the pions $m_\pi = 140$ MeV. In an ideal case both values derived for γ should agree. However, a comparison of the values obtained for different energy bins, as shown in Fig. 2, exhibits that the quantities differ by a factor of about 4. On the other hand it is quite interesting to realize that such a simple approach delivers results within the expected order of magnitude.

The attenuation lengths obtained applying the different methods yield values between about 100 g/cm^2 and $\approx$ 250 g/cm^2. It is obvious that the different methods yield different attenuation lengths. In particular, they are not expected to agree with the interaction lengths for pions and/or protons.

Nevertheless, to give a hint towards the expected magnitude of the attenuation lengths in Fig. 1 also expectations according to a hadronic interaction model are shown. The open symbols represent the proton-air λ_{p-air} and pion-air $\lambda_{\pi-air}$ interaction lengths according to the model QGSJET 01 [7]. Over the three decades shown they decrease slightly with energy starting with $\lambda_{p-air} \approx 90$ and $\lambda_{\pi-air} \approx 120$ g/cm^2 at 100 GeV. In the analyses presented, the measured hadrons are treated as surviving primary particles. However, in reality, the "unaccompanied hadrons" are mostly the debris of small air showers interacting in the upper atmosphere. Hadrons reaching ground level have undergone about two to five interactions. Thus, the measured attenuation lengths are larger as compared to the interaction lengths of the particles in the model.

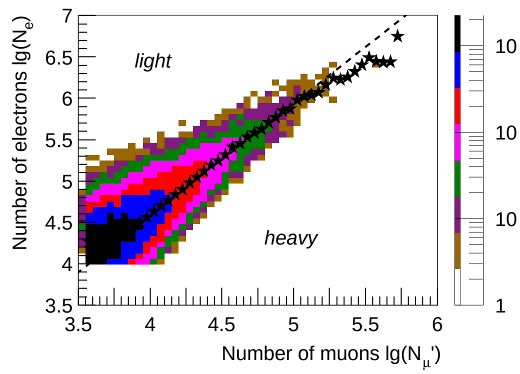

Figure 4: Number of electrons and muons for the measured showers.

Hadrons in Air Showers

The second part deals with hadrons in air showers. The primary energy E_0 of the shower inducing particle is roughly estimated based on the number of electrons N_e and muons N'_μ registered with the KASCADE field array: $\lg E_0 \approx 0.19 \lg N_e + 0.79 \lg N'_\mu + 2.33$. The "surviving energy" in form of hadrons ΣE_H is measured with the hadron calorimeter. Thus, a fraction $R = \Sigma E_H/E_0$ of hadronic energy reaching ground level can be inferred as function of primary energy as shown in Fig. 3. In the energy range investigated about 0.1% to 0.35% of the primary energy reach the observation level in form of hadrons. With an average elasticity $\epsilon \approx 0.25$ [8] and $R = \epsilon^N$ the average number of generations N in the shower can be estimated and it turns out that the registered hadrons have undergone about four to five interactions.

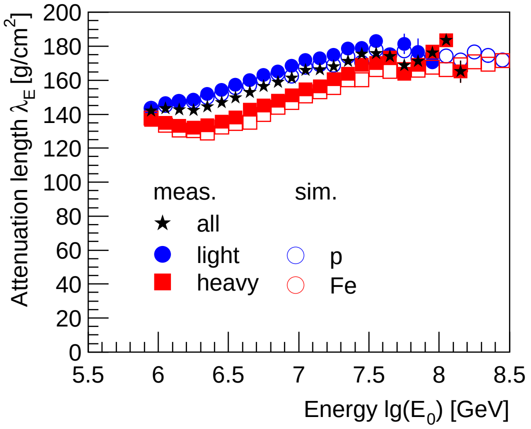

Figure 5: Attenuation length λ_E as function of estimated primary shower energy.

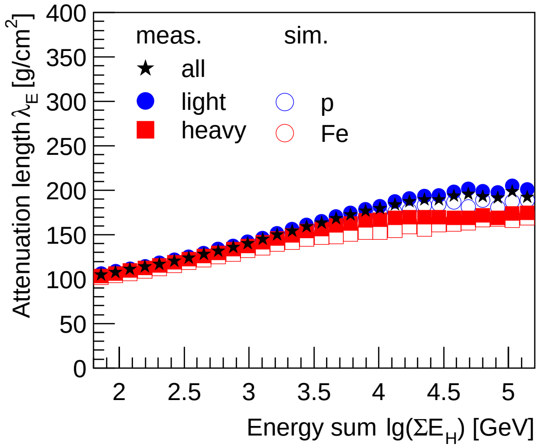

Figure 6: Attenuation length λ_E as function of the measured hadronic energy sum at observation level.

The two-dimensional distribution of the number of electrons and muons for the measured showers is depicted in Fig. 4. The asterisks represent the most probable values of the distribution. The dashed line, obtained by a fit to the most probable values is used to separate the registered data into a "light" and "heavy" sample. The energy fraction reaching observation level is shown in Fig. 3 as well for the light and heavy primaries. As expected from a simple superposition model, proton-like showers transport more energy to the observation level as compared to iron-like showers.

An attenuation length λ_E has been derived from the measured energy fraction assuming $\Sigma E_H = E_0 \exp(-X_0/\lambda_E)$. The results are presented as function of the estimated primary energy in Fig. 5. Values for the complete data set as well as for the light and heavy selection are shown. The values are compared to results obtained from full air shower simulations for primary protons and iron nuclei using the CORSIKA program with the hadronic interaction generators FLUKA [9] and QGSJET 01. It can be seen in the figure that the results for the light and heavy selections agree well with the values for primary protons and iron nuclei, respectively.

Instead of the primary energy the results can also be calculated as function of the hadronic energy sum at observation level. The values thus obtained can be compared to the previous results shown in Fig. 1. However, it should be pointed out that λ_E is yet another definition for an attenuation length. The results for all data, as well as for the light and heavy selection are presented in Fig. 6. Again, the measured attenuation lengths are compared to simulations for primary protons and iron nuclei and a reasonable agreement between measured and simulated values can be stated.

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