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Attenuation and Absorption Lengths of EAS measured with the KASCADE Experiment

G. Maier[1], T. Antoni[1], W.D. Apel[1], F. Badea[2], K. Bekk[1], A. Bercuci[1,2], H. Blümer[1,3], E. Bollmann[1], H. Bozdog[2], I.M. Brancus[2], C. Büttner[1], A. Chilingarian[4], K. Daumiller[3], P. Doll[1], J. Engler[1], F. Feßler[1], H.J. Gils[1], R. Glasstetter[3], R. Haeusler[1], W. Hafemann[1], A. Haungs[1], D. Heck[1], J.R. Hörandel[3], T. Holst[1], A. Iwan[3,5], K-H. Kampert[1,3], J. Kempa[5,+], H.O. Klages[1], J. Knapp[3,¶], H.J. Mathes[1], H.J. Mayer[1], J. Milke[1], M. Müller[1], R. Obenland[1], J. Oehlschläger[1], M. Petcu[2], H. Rebel[1], M. Risse[1], M. Roth[1], G. Schatz[1], H. Schieler[1], J. Scholz[1], T. Thouw[1], H. Ulrich[3], B. Vulpescu[2], J.H. Weber[3], J. Wentz[1], J. Wochele[1], and J. Zabierowski[6]

[1]Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany
[2]National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania
[3]Institut für Experimentelle Kernphysik, University of Karlsruhe, 76021 Karlsruhe, Germany
[4]Cosmic Ray Division, Yerevan Physics Institute, Yerevan 36, Armenia
[5]Department of Experimental Physics, University of Lodz, 90236 Lodz, Poland
[6]Soltan Institute for Nuclear Studies, 90950 Lodz, Poland
[+]now at: Warsaw University of Technology, 09-400 Plock, Poland
[¶]now at: University of Leeds, Leeds LS2 9JT, U.K.

Abstract.

An analysis of attenuation and absorption lengths of the electron number using data of the KASCADE air shower experiment is presented. The following methods are used to determine these quantities: The method of constant intensity, the attenuation of the electron number at the knee with increasing atmospheric depth, the decrease of the flux at a constant electron number with increasing zenith angle and the variation of the flux with ground pressure. The differences in the results are explained with respect to methodical uncertainties. An estimation of the influence of intrinsic shower fluctuations on the results is given.

Attenuation lengths between 175 and 196 g/cm^2 and absorption lengths between 100 and 120 g/cm^2 depending on electron number are obtained.

1 Introduction

The longitudinal development of the electromagnetic part of extensive air showers (EAS) is characterized by an approximately exponential decrease in particle numbers for atmospheric depths far behind the shower maximum. This decline is described by the attenuation length Λ_{N_e}, the variation of the rate at fixed electron number with atmospheric depth by the absorption length Λ_{rate}.

The definitions are for the attenuation length:

$$N_e(X) \propto \exp\left(-X/\Lambda_{N_e}\right) \qquad (1)$$

and for the absorption length:

$$j(> N_e, X) \propto \exp\left(-X/\Lambda_{rate}\right) \qquad (2)$$

where $N_e(X)$ describes the electron number at atmospheric depth X in the usual unit of g/cm^2 and $j(> N_e, X)$ the rate of showers with more than N_e electrons at given depth.

The absorption length depends on the form and the steepness of the primary energy spectrum, while the definition of the attenuation length is independent of that. The commonly used conversion of Λ_{rate} into Λ_{N_e} by multiplying Λ_{rate} with the spectral index is only valid with the assumptions of a primary energy spectrum following a power law with constant spectral index, a composition of only one primary component and no intrinsic shower fluctuations.

Λ_{N_e} and Λ_{rate} depend on absorption and production rates of the electromagnetic particles and therefore on the hadronic interaction. The most important hadronic quantities in this context are the cross-sections and inelasticities, which are not well know from accelerator experiment at EAS energies. Detailed measurements of the attenuation and absorption lengths as functions of electron number make it possible to study these quantities by comparing them with simulations of EAS.

2 Experiment and reconstruction

The KASCADE experiment located at the Forschungszentrum Karlsruhe, Germany (110 m a.s.l.), is designed to measure with its multi-detector setup a variety of observables of EAS (Klages et al., 1997). KASCADE consists of three ma-

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Correspondence to: G.Maier (maier@ik1.fzk.de) jor detector systems, a large field array, a muon tracking detector and a central detector.

In the present analysis data from the 200x200 m^2 scintillator array are used. The 252 detector stations of the array are uniformly spaced on a grid with a separation of 13 m. Each station in the inner part of the array contains liquid scintillator detectors to measure the electromagnetic component, those of the outer part contain additionally under a shielding of iron and lead a plastic scintillator to measure the number of muons. Detailed description of the detectors is given by Doll et al. (1990) and Antoni et al. (2001).

The iterative shower reconstruction procedure determines the electron number N_e mainly by maximizing a log-likelihood functional with the NKG formula. For the number of electrons N_e the signals in the detectors are corrected for contributions of other particles like γ's, μ's and hadrons. Shower directions are determined by fitting a conical shower front to the measured arrival times. A more detailed presentation of the reconstruction methods can be found in Antoni et al. (2001).

A total number of about 40 Mio. showers, covering the time between May 1998 and December 1999, enter into the analysis.

3 Methods

3.1 Method of constant intensity

The idea behind the method of constant intensity (Nagano et al., 1984) is to select showers with same primary energy and then observe their attenuation with increasing atmospheric depth. Assuming a direct connection between the primary energy spectra and the electron number spectra, application of equal intensity cuts to integral electron number spectra in different angular bins select showers with approximately equal primary energy. Measuring the attenuation of the electron number with increasing zenith angle yields Λ_{N_e}.

3.2 Attenuation of the electron number at the knee

Assuming that the knee in the electron number spectra is a consquence of a knee in the primary energy spectrum, the shift of the position of the knee with increasing atmospheric depth is a measure of the attenuation of the electron number.

This is in a sense a special case of the method of constant intensity, but the shape of the electron number spectra are influenced by intrinsic shower fluctuations. The knee positions are shifted in a nontrivial way towards larger electron numbers, the assumption of constant flux at the knee is therefore only approximately correct.

The knee positions are fitted in the present analysis with the following function (Glasstetter et al., 1997):

$$dj/dN_e \propto \begin{cases} N_e^{-\gamma_1} \\ N_e^{-\gamma(N_e)} = N_e^{a_2 \log N_e + a_1} \\ N_e^{-\gamma_2} \end{cases} \qquad (3)$$

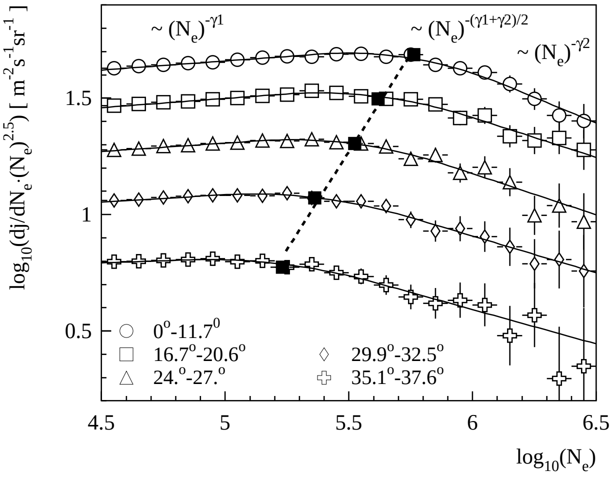

Fig. 1. Knee region of the differential electron number spectra for five intervalls in zenith angle. Knee-positions are indicated by the filled squares. Solid lines show the fits described in the text. Only spectra of every second angular bin are plotted.

The respective function is valid in a region below the knee ($\log N_e \le \log N_{e,k} - \epsilon$), in the knee region ($\log N_{e,k} - \epsilon < \log N_e < \log N_{e,k} + \epsilon$) and above the knee ($\log N_e \ge \log N_{e,k} + \epsilon$). The half-width of the knee region is fixed at $\epsilon = 0.38$ on a logarithmic electron number scale. The coefficients a_1 and a_2 are determined by the condition that the function and its first derivative are continuous.

3.3 Absorption length - angular method

The absorption length is determined from the integral electron number spectra by analysing the decrease of the shower rate at a constant electron number with increasing atmospheric depth.

The results of this methods are obviously sensitive to the knee in the electron number spectra. This knee effect (Bourdeau et al., 1980) appear due to the different occurrence of the change in the spectral index in the electron number spectra in different angular bins. Therefore only the absorption lengths above the knee region have physical significance.

3.4 Absorption length - barometric method

The influence of atmospheric ground pressure was analysed by counting the number of showers above a certain electron number in two hour time intervals. The atmospheric ground pressure varies only little within these time intervals. The decrease of the intensity with increasing ground pressure yields the absorption length.

The major difference between the angular and barometric method is the amount of variation in atmospheric depth. While in the angular method it is about 300 g/cm^2, it is only about 30 g/cm^2 in the barometric method. This allows a precise scanning of the longitudinal development in different atmospheric depths.

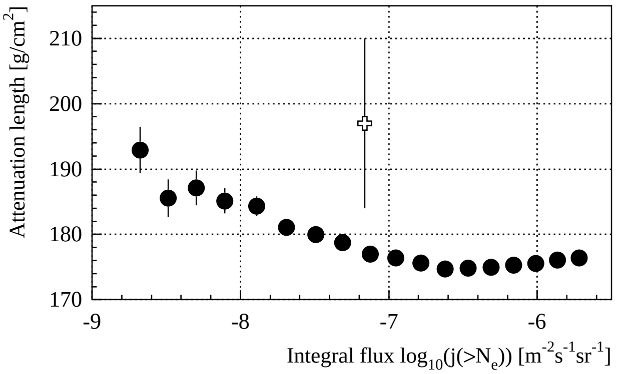

Fig. 2. Attenuation lengths Λ_{N_e} determined by the method of constant intensity (filled circles) and the attenuation of the electron number at the knee (open cross).

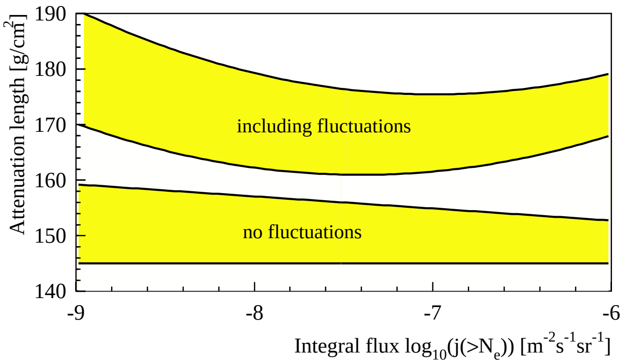

Fig. 3. Attenuation lengths from simulated electron number spectra determined with the method of constant intensity. The shaded region reflects the uncertainties due to the choice of the input parameters.

4 Results

4.1 Attenuation length

The differential electron number spectra of KASCADE are shown in Figure 1 for five intervalls of zenith angle. The attenuation of the knee position is indicated by the dashed line, resulting in $\Lambda_{N_e} = 197 \pm 13$ g/cm^2. The quoted error is of statistical kind. The systematic error is difficult to estimate, but at least of the order. For example, a simple fit of the spectra by two straight lines and taking the knee position at their intersection yields an attenuation length of about 170 g/cm^2. The attenuation length depends therefore strongly on the method used to determine the position of the knee.

Figure 2 shows the resulting attenuation lengths from the method of constant intensity as a function of integral flux. Λ_{N_e} increases with decreasing flux, i.e. with increasing primary energy. This is on the one side due to deeper penetration of showers with higher energy into the atmosphere, on the other side an effect of the modification of the electron number spectra by intrinsic shower fluctuations (see following section).

The large difference in value and error between the result from the knee position and the method of constant intensity comes in parts from the uncertainties resulting from the fit of the electron number spectra.

4.2 Influence of intrinsic shower fluctuations, reconstruction accuracy and detector response

The method of constant intensity is sensitive to the form of the electron number spectra. Intrinsic shower fluctuations, reconstruction accuracy and detector response modify this form. These effects were studied by simulations. The EAS are simulated with the CORSIKA package (Heck et al., 1998). The reconstruction accuracy and detector efficiencies are determined by a detector simulation based on GEANT (GEANT , 1993).

For this analysis, trial electron number spectra with intrinsic shower fluctuations, reconstruction accuracy and the detector response switched off and on are produced in the same angular bins as the data. The energy spectra assumed in the simulations are taken from a previous analysis of KASCADE (Glasstetter et al., 1999).

The trial electron number spectra were analysed with the method of constant intensity in the same manner as the data. Figure 3 shows the resulting attenuation length. The lower region shows attenuation lengths determined from the trial electron number spectra without any fluctuations and detector influences, the upper region with all effects included. The shaded regions reflect the uncertainties due to the choice of the input parameters for the simulation, i.e. of the spectral indices, composition and parametrisations of the fluctuations.

Several effects can be seen. First, all attenuation lengths are shifted by about 15-30 g/cm^2 towards higher values. Second, they are increasing at high fluxes. This is due to the poorer reconstruction accuracy for very small showers. The rise of the attenuation lengths for low fluxes is caused by intrinsic shower fluctuations, only. Comparison of figure 3 with figure 2 shows that the simulation is not fully in agreement with the results from the data. This is thought to be due to the simplified assumption in the parametrisation of the intrinsic shower fluctuation by Gaussian functions on logarithmic electron number scale.

Figure 3 demonstrates, that the results of the method of constant intensity are strongly influenced by fluctuations. Any interpretation of the presented attenuation lengths has to take shower fluctuations into account. We gues that the results of all other methods are influenced by fluctuations in the same order of magnitude.

4.3 Absorption length

The results of the analysis of the absorption length Λ_{rate} are shown in figure 4. The cross hatched region expresses the influence of the knee structure in the shower number spectra. As mentioned before, these values of Λ_{rate} are biased by the

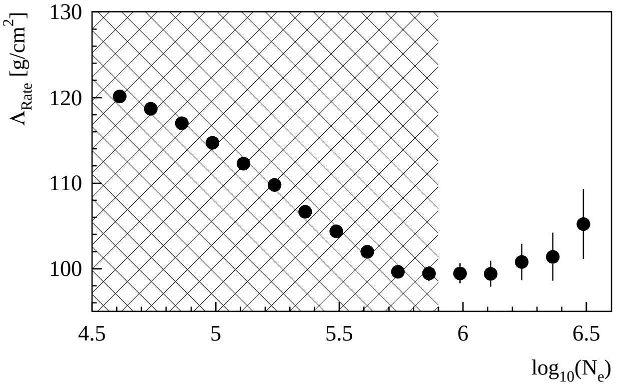

Fig. 4. Absorption length versus electron number determined by the angular method. The cross hatched background indicates the region influenced by the knee.

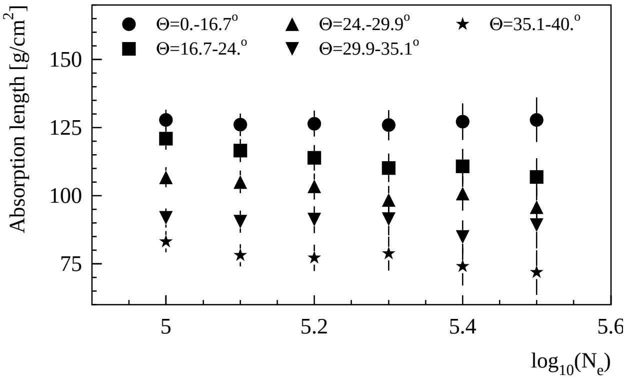

Fig. 5. Absorption length for showers with different zenith angles determined by the barometric method.

different knee positions of spectra in different zenith angles. Above the knee, the absorption length increases like the attenuation length (see also Nagano et al. (1984)). The rough estimation of Λ_{N_e} from Λ_{rate} by $\Lambda_{rate} = \Lambda_{N_e} \cdot \gamma_2^{integral} \approx \Lambda_{N_e} \cdot 1.8$ is consistent with the attenuation lengths in Figure 2.

The barometric method yields absorption lengths in different atmospheric depths. Λ_{rate} decreases with increasing zenith angle (Figure 5), i.e. the longitudinal development deviates from an exponential form and becomes steeper with increasing atmospheric depth.

Since observation time is about 19 months, no seasonal influence on the described results is expected.

5 Conclusion

We presented measurements of the atmospheric attenuation of the electromagnetic component in EAS. An increase of the attenuation length with increasing energy follows from the method of constant intensity as well as from measurements of absorption lengths. The effect of shower fluctuations on the results is significant and shifts the attenuation lengths by about 15-30 g/cm^2. Deviations from the exponential form of the attenuation are shown by the barometric method.

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References

Antoni, T., et al., KASCADE Collaboration, *Astrop.Phys*, **14**, 245-260, 2001 .

Bourdeau, M.F., et al., *J.Phys.G:Nucl.Phys.* **6**, 401-410, 1980.

CERN Program Library Long Writeup **W5013**, CERN, Genf, 1993.

Doll, P., et al., KASCADE Collaboration, Kernforschungszentrum Karlsruhe, Report **KfK 4648**, 1990.

Glasstetter, R., et al., KASCADE Collaboration, *Proc. 25th Int.Cosmic Ray Conf.*, Durban, **2**, p.157, 1997.

Glasstetter, R., et al., KASCADE Collaboration, *Proc. 26th Int.Cosmic Ray Conf.* Salt Lake City, **1**, p.222, 1999.

Heck, D. et al., Forschungszentrum Karlsruhe, Report **FZKA 6019**, 1998.

Klages, H.O., et al., KASCADE Collaboration, *Nucl.Phys.B (Proc.Suppl.)* **52B**, 92-102, 1997.

Nagano, M., et al., *J.Phys.G:Nucl.Phys.* **10**, 1295-1310, 1984.

Nagano, M., et al., *J.Phys.G:Nucl.Phys.* **10**, L235-L239, 1984.