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# Investigation of extensive air shower development using large slant depth of atmosphere

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**Abstract.** Using the EAS size spectra measured with the MAKET ANI array on on Mt. Aragats, Armenia ($3200m$ a.s.l., $700g \cdot cm^{-2}$) in the range $N_e = 10^5 - 10^7$ for different angles-of-incidence, the EAS attenuation length has been determined applying different analysis methods. Energy dependence of the attenuation length at large slant depth of atmosphere ($700 - 1250g/cm^2$) is obtained and discussed.

## 1 Introduction

The attenuation of the flux intensity of Extensive Air Showers (EAS) is characterized by a parameter $\lambda_N$ *(intensity attenuation length, absorption)*, which can be directly measured by cosmic rays detector arrays located at different atmospheric depths. On the other hand the parameter $\Lambda$ controls the attenuation of particles of the individual cascade (Hayakawa S., 1969) *(size attenuation length)*.
The estimate of the attenuation length is obtained by fitting the shower size $N_e$ dependence on the depth in atmosphere by the straight line (in double logarithmic scale) according to the equation:

$$N_e(X) = N_e(X_0) exp\left(-\frac{X - X_0}{\Lambda}\right), \quad \text{with } X \geq X_0. \quad (1)$$

$X_0$ is a definite initial atmospheric depth after the maximum of the longitudinal development where the number of (charged) particles is $N_e(X_0)$ and further decreasing exponentially, $N_e(X)$ is the number of particles of the EAS at the slant depth $X[g \cdot cm^{-2}]$.

Measurements of the attenuation and absorption length are considered to be an interesting source of information about hadronic interactions, especially if extended to the ultrahigh energy region expected from the forthcoming LHC and TESLA accelerators. In addition due to the sensitivity of the cross sections to the mass of the primary, alterations of the attenuation length with the energy may be indicative for the variations of the mass composition. Measured results also imply tests of the energy dependence of the extrapolated cross sections used for Monte Carlo simulations.
We apply different procedures to deduce the attenuation. First we consider the degradation of the EAS flux with fixed shower size $N_e$ with increasing zenith angle i.e. increasing atmospheric thickness of the shower development (characterized by the intensity attenuation length ($\lambda_N$) (Khristiansen B. G., et al., 1975)). Differently the technique of the constant intensity cut (CIC) (Nagano M. et al., 1984) considers the intensity spectrum of EAS events and relates equal intensities observed at different atmospheric depths for obtaining cascade curves.

## 2 EAS size Spectra

The results of the present report are based on an EAS sample measured 1997-2000 with the MAKET ANI array (Avakyan V. V. et al., 1993; Hovsepyan G. G. for the ANI Collaboration, , 1998). Details of the measurements and the experimental procedures are given elsewhere (Gharagyozyan G. V. for the ANI Collaboration, , 1998; Blokhin S. V., Romakhin V. A., Hovsepyan G. G., 1999).

For the analysis of the zenith-angle dependence, the size spectra are determined in 5 angular bins of equal $\Delta \sec \Theta$ which correspond to an absorber thickness of $\approx 60g/cm^2$ in each bin (for details of MAKET ANI size spectra see (Stanev T., 1999)). The accuracy of the zenith angle determination is estimated to be about $1.5°$ (Gharagyozyan G. V. for the ANI Collaboration, , 1998). The data basis of the analysis was enlarged by published data from KASCADE ($1020\, g \cdot cm^{-2}$) (Klages H. O. et al.,, 1998) experiment.
By method (Sokhoyan S. H. for the ANI Collaboration, 1998) of spectra fitting the slopes of the spectra below ($\gamma_1$) and above ($\gamma_2$) the knee, the knee position $N_{e_k}$ were determined. Same method was used for approximation of KASCADE

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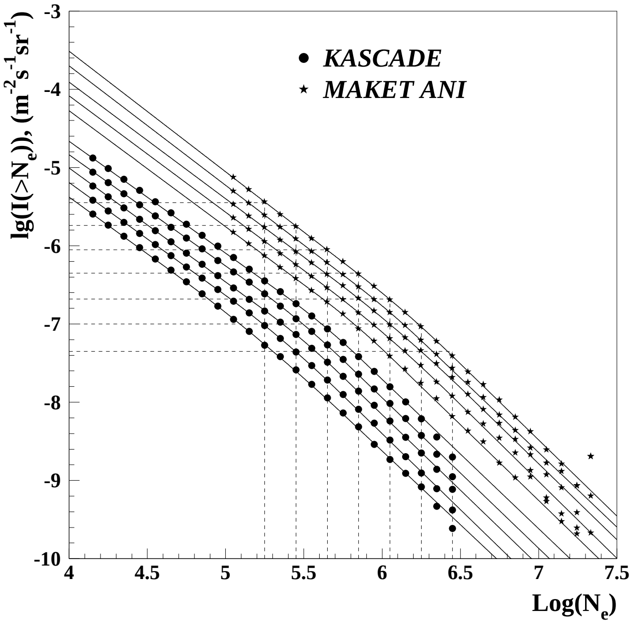


**Fig. 1.** *Integral size spectra for different zenith angles observed with MAKET ANI array, compared with spectra reported by the KASCADE (Glasstetter R. for the KASCADE Collaboration, 1998)*

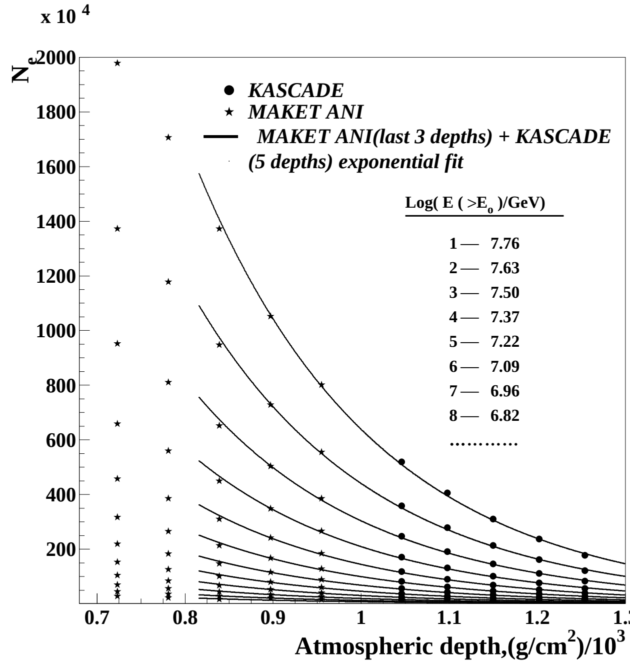


**Fig. 2.** *$N_e$ cascade in the observed range of the atmospheric slant depth for different energies.*

data, too. Denote, that the investigated interval of KASCADE data (Glasstetter R. for the KASCADE Collaboration, 1998) is $\Theta = 0 - 37.4°$ and the width of absorber thickness is thus $\approx 50g/cm^2$ in each bin.

## 3 Which Primary Energies We Selected by CIC Method?

The basic idea of CIC Method is to compare the average size of showers which have the same rate (showers per $m^2 \cdot s \cdot sr$) in the different bins of the zenith angle of shower incidence and different slant depth, respectively (Nagano M. et al., 1984).
By the different fixed intensities of the size spectra the cascade curves (shower size dependence on the atmospheric depth for fixed primary energy) can be immediately reconstructed for several fixed flux intensities (primary energies) as shown in Figure 1 .

The tacit assumption that by cutting on the same EAS size spectra intensities, we chose approximately constant primary energy was checked during pilot study with simulated samples. CORSIKA 562 code (Heck D. et.al.,, 1998) was used for simulation of EAS traversed through atmosphere.
Figure3 a) demonstrates the distribution of the primary energies of events falling in the size spectra bins correspondent to different horizontal cuts of experimental size spectrum for the first zenith angles interval $(0^o - 22.6^o)$. The variances of the energy distributions, correspondent to different intensity are decreasing with increasing of energy. Figure 3 b) depicts the ”selected energies” distributions for fixed EAS flux intensity and different angles of incidence. The unbiasness of distributions mode proves that by ”cutting” spectra we are choosing EAS events, corresponding to approximately same primary energies. Figure 3 c) demonstrates the relative errors of assigned energies. Increasing of errors with increasing of zenith angles is evident. On altitude 3200 m. primary energy variance of ”cutted” events didn't exceed 50%. Figure 3d) shows dependencies of spectra intensities on correspondent mean energies for five zenith angle intervals. Good coincidence of these curves for all zenith angles proves soundness of CIC procedure. The issue of measuring integral energy spectra will be considered elsewhere (A. A. Chilingarian et al.,, 2001)

## 4 Procedures for Inference of the Attenuation Length from size spectra

We consider the differential and integral size spectra $I(N_e, X)$ and $I(> N_e, X)$, respectively. In addition to the basic assumption of exponential attenuation of $N_e$ (eq.1) a power-law dependence of the size spectrum with the spectral index $\gamma$ is adopted.

### 4.1 Attenuation of the Intensity of Fixed $N_e$: Absorption Length

For different fixed values of shower size $N_e$, on different depths in the atmosphere (or/and different zenith angles of incidence), from measured spectra we obtain several values of corresponding intensities from the equivalent depths from 700 till 1280 $g \cdot cm^{-2}$ (see Figure 3). By fitting the depth dependence of the intensities by the straight line (in logarithmic

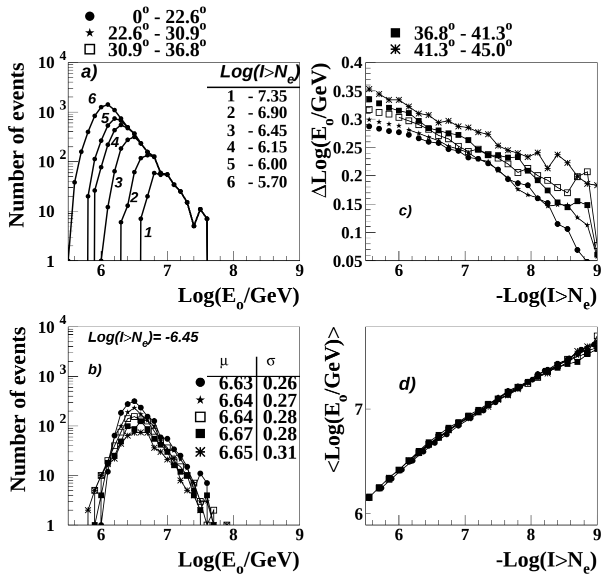


**Fig. 3.** *Fluctuations of energy for different integral intensities and zenith angles*

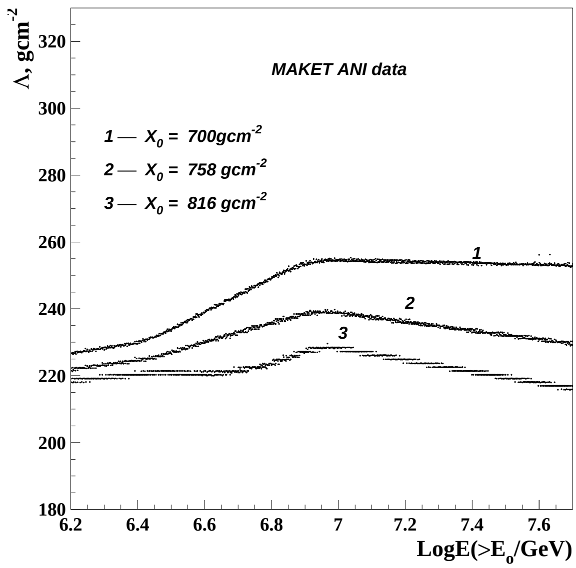


**Fig. 4.** *Attenuation Length dependence on Primary Energy.*

scale) according to equation:

$$I(N_e, X) = I(N_e, X_0) exp\left(-\frac{X - X_0}{\lambda_N}\right) \tag{2}$$

we obtain the estimate of the absorption length $\lambda_N$. The absorption length can be estimated both by integral and differential spectra.

### 4.2 The Relation Between the Absorption and Attenuation Lengths

We consider the quantity $I(N_e, X)dN_e$ - the number of EAS at the depth $X$ which comprise $N_e$ to $N_e + dN_e$ particles fallen in ($N_e$-$N_e$+d$N_e$) interval:

$$I(N_e, X)dN_e \sim N_e^{-\gamma} exp\left[-(\gamma - 1)\frac{X - X_0}{\Lambda}\right] dN_e \tag{3}$$

With eq.2 we obtain:

$$\Lambda_{diff}(N_e) = (\gamma(N_e) - 1)\lambda_N, \tag{4}$$

where, $\gamma(N_e)$ is the differential size spectra index (therefore, for $\lambda$ estimation we have to use the $N_e$ intervals where $\gamma$ is not changing dramatically). For the integral spectra:

$$\Lambda_{int}(N_e) = \gamma(N_e)\lambda_N, \tag{5}$$

where, $\gamma(N_e)$ is integral size spectra index.

## 5 Estimation of the Attenuation Length

As we can see in Figure 2, the values corresponding to the minimal equivalent depths of used MAKET ANI data, deviate significantly from the exponential dependence. The observations reflect the flattening of the cascade curve just after the shower maximum, expected at the altitudes $500 - 600\, g \cdot cm^{-2}$. Therefore, due to these features the attenuation lengths calculated by MAKET ANI data appear to be significantly larger than those derived for the KASCADE data.
Consequently, for the combined analysis of the KASCADE and ANI data we omitted the first and the second zenith angle bins of MAKET ANI and calculate the attenuation lengths by the remaining 9 (minimal equivalent depth $758\, g \cdot cm^{-2}$) and 8 (minimal equivalent depth $816\, g \cdot cm^{-2}$) angular bins. The dependence of estimated value of attenuation length on the primary energy for different amount of the angular bins used, is displayed in Figure 4. The attenuation length estimates obtained from the differential and integral spectra agree fairly well. The results of both CIC and recalculation from absorption length agree within the error bars.
By taking the advantage of the precise measurements of the cascade curves by KASCADE and ANI detectors we fit joint data with one decay parameter for the first time (see Figure 5). The "knee" position, obtained by fitting of the size spectra, also are posted on the picture. There is a concentration of the knee positions on the curve showing the dependence of the attenuation on the primary energy. In its turn, the curve displaying the dependence of the attenuation length on the shower size demonstrates a rather large dispersion of the "knee positions". Interpretation and physical inference based on the obtained results will require detailed simulation of cascade development in atmosphere and detector response

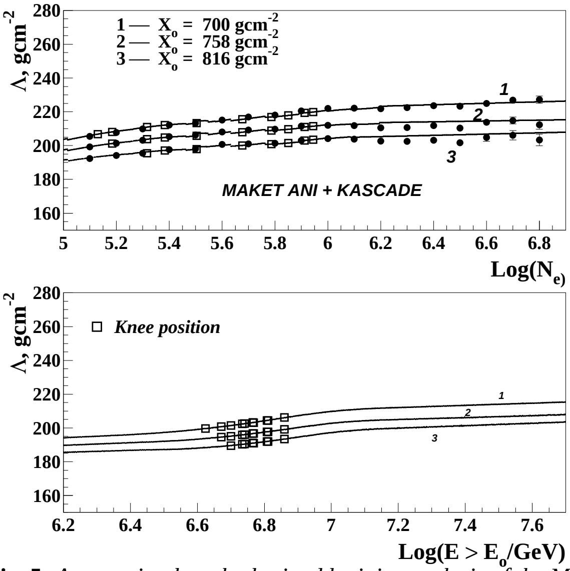


**Fig. 5.** *Attenuation length obtained by joint analysis of the MAKET ANI and KASCADE data.*

now underway.

## 6 Conclusion

Experimental studies of EAS characteristic like the depth of the shower maximum $X_{max}$, the elongation rate $dX_{max}/dlog_{10}E$ and the attenuation length $\Lambda$ are of particular importance, since they map rather directly basic features of the hadronic interaction. However, the interpretation of these quantities in terms of hadronic cross sections cannot bypass the necessity of detailed calculations of the shower development. Nevertheless these type of EAS quantities, if compared with Monte Carlo simulation results, provide stringent tests of the interaction model used in simulations.
The recent results of various experimental installations are sufficiently accurate to enable relevant studies of this kind, and combining the data from arrays situated on different altitudes (like MAKET ANI and KASCADE) allows a large span in the atmospheric slant depth for reconstructing the longitudinal development of the EAS.

By use of methods to isolate different primary groups ("pure nuclear beams") of the size spectra (Chilingarian A. A., Roth M. and Vardanyan A. A. for the KASCADE collaboration, 1999), these kind of interaction studies would get of extreme interest.

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