Arrival Time Distribution of Cerenkov Photons and the Elemental Composition of Primary Cosmic Rays Around 10^{15} eV

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Abstract

The mean depth of the shower maximum for extended air showers depends on the mass of primary nucleon and the primary energy. The depth can be deduced from the arrival time distribution (FWHM) of air Cerenkov photons if measured at large distances from the shower axis. Measurements with Flash ADC's at the HEGRA experiment are presented.

1 INTRODUCTION

The elemental composition of primary cosmic rays around and above 10^{15} eV (the knee) is of great importance for the understanding of the origin and acceleration mechanism of charged cosmic rays but is still not well known and even controversial. It is so far only accessible to indirect measurements. In those measurements the energy and the mass of the primary particle has to be determined simultaneously from the extended air shower. Therefore a multiparameter measurement of the air shower is needed.

New methods are presently developed to exploit a multiparameter measurement of Cerenkov light (intensity and shape of lateral distribution) and charged particles (Ne and age) as obtained by the HEGRA experiment in order to determine the primary energy and the composition. The methods applied to the data are presented in more detail in other contributions to this conference [1] [2].

In the article presented here those quantities from Cerenkov light measurements are addressed which are sensitive to the depth of the shower maximum in the atmosphere and play therefore an important role in methods for the determination of the composition. These quantities are the shape of the lateral distribution of the Cerenkov light (at distances from 20 - 100 m from the shower axis) and the arrival time of Cerenkov photons at larger distances. Specifically the latter quantity is addressed in more detail below.

The sensitivity of the arrival time distribution to the shower maximum is due to the fact that the Cerenkov light emitted in early stages of the shower development arrives early if measured at large distances to the shower axis as compared to light emitted at later stages. In this way the longitudinal development is mapped onto a temporal sequence. This is well known and has been investigated theoretically and experimentally by several groups. ([3] [4] [5] [6]). The aim of the present work is to measure showers with energies as low as $5 \cdot 10^{14}$ eV. This necessitates measurements at

[1] for a complete author list see F.Aharonian et al. these proceedings, presented by V. Fonseca

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rather small distances of 120 - 200 m from the shower axes due to the lateral intensity falloff, although the sensitivity to the longitudinal development would be higher at large distances.

2 EXPERIMENTAL SETUP

The data presented here were collected with the HEGRA arrays consisting of a matrix of 219 scintillators ($1m^2$) in a 15 m and 10 m grid and a matrix of 49 wide angle Cerenkov counters (30 m grid). These arrays are located in an area of 180 x 180 m^2 at La Palma (2200 ma.s.l.) and are described in detail elsewhere [7] [8]. Three additional large diameter photomultipliers (AIROBICC counters [8]) were placed outside the detector field at distances of 180 m (2 counters) and 220 m (1 counter) to the array center in order to measure the arrival time distribution of the Cerenkov photons. The signals of those three counters were digitized each with two fast Flash-ADC's with sampling rates of 250 MHz and 1 GHz and partially overlapping dynamic ranges for pulse height measurements. Also 4 counters inside the array were equipped with Flash ADC's and used to determine the detector resolution and stability.

The Flash-ADC system was operated in a common stop mode i.e. the PM signals were continuously digitized and stored in a cyclic buffer with a depth of 256 (1024). Each time an array trigger occurred (20 Hz) the digitizing process was stopped and the relevant data in the cyclic buffer were read out via VME and a McIntosh and stored on EXABYTE tape, than the digitizing process was started again. No additional deadtime was introduced.

3 MONTE CARLO SIMULATIONS

In order to interpret the measurements a Monte Carlo simulation with the program package CORSIKA 4.01 ([9]) developed by the KASCADE Collaboration was used with an addition for the Cerenkov light production. In total 308 showers were

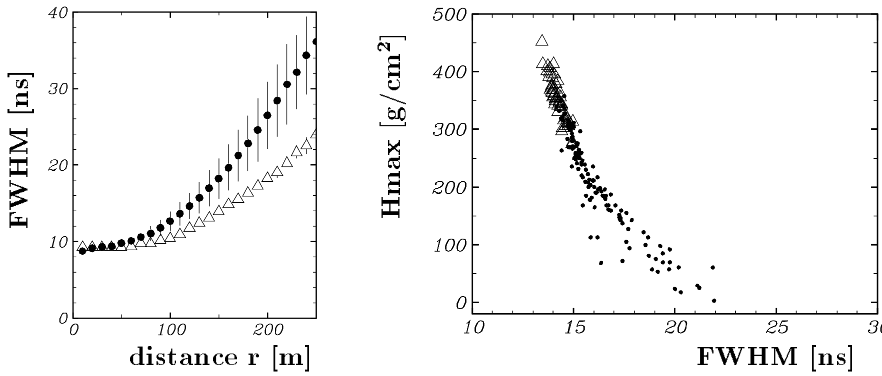

Figure 1: *Monte Carlo simulation for the detection level of 2200m (793 gr/cm^2)*
(a) Mean width (FWHM) of the arrival time distribution as a function of the distance r to the shower axis for proton (•) and iron nuclei (△) around 1 PeV.
(b) Height of shower maximum above detection level as a function of the width (FWHM) of the arrival time distribution at 150 m from the shower axis.

generated in the energy interval from 5 $\cdot 10^{14}$ eV - 5 $\cdot 10^{15}$ eV and zenith angles of 0^o and 15^o for p, α, O, and Fe nuclei.

The response of the AIROBICC counter to the Cerenkov light i.e. the detector resolution function has been determined from the data such that the Monte Carlo data folded with the resolution function reproduces the pulse shape at small distances since at small distances ($\leq$ 50 m) the width of the Cerenkov light arrival time of 1 - 2 ns is much smaller than the width of the detection system of $\sim$ 7.4 ns [10]. The resolution function includes all detector effects relevant for the measurement of the arrival time distribution.

The FWHM of the arrival time distribution obtained from the Monte Carlo simulation, after folding with this resolution function, are shown in Fig. 1a as a function of the distance r to the shower axis. The two curves correspond to proton and iron initiated showers. The error bars denote the variance of the shower height distribution. The dependence of the FWHM as a function of the distance r has been parametrized with an empirical formula (polynomial and exponential) with only two free parameters. This dependence is used to relate the measurements at different distances from the shower axis to a fixed distance chosen to be 150 m.

The correlation of the FWHM at a distance of 150 m with the height of the shower maximum is shown in Fig.1b. Interesting to note is the long tail towards large FWHM which is due to protons penetrating deep into the atmosphere.

4 DATA

The data were recorded during about 20 moonless nights in 1994. The shower directions from both arrays and the lateral distributions were reconstructed e.g. a fit to the lateral distribution of the Cerenkov light of the form e^{-R/R_L} in the range from 20 - 100 m gives the so called light radius R_L. The Cerenkov pulse shapes digitized with Flash-ADC's were fit with spline functions and than the FWHM were determined. Requiring zenith angles $\leq$ 15 degrees and well determined shower cores inside the arrays 3000 events remained with shower sizes N_e in the range from $5 \cdot 10^4$ to 10^6 used for the analysis presented here.

5 RESULTS

The correlation of the measured FWHM and the measured slope parameter R_L defined above is shown in Fig. 2a. As mentioned above, apart from the FWHM of the arrival distribution, also the shape of the lateral intensity distribution is a measure of the height of the shower maximum. A good correlation can be observed which is well reproduced by Monte Carlo simulation if detector effects are taken into account. To our knowledge this is the first time that a correlation of this type is shown from the data. It should be mentioned, that very different experimental procedures and therefore uncertainties enter in this correlation. Wheras the lightradius R_L depends on a good intensity measurement i. e. stability and calibration of 49 detector gains, the arrival time distribution depends on pulse shape measurement and good knowledge of the detector response function. It thus constitutes also an important experimental cross check.

In Fig. 2b the width as measured by a single counter is shown as a function of the distance to the shower axis. Work is in progress using the energy determination as presented in [1] in order to evaluate the measured widths and their spread for well defined energy intervalls.

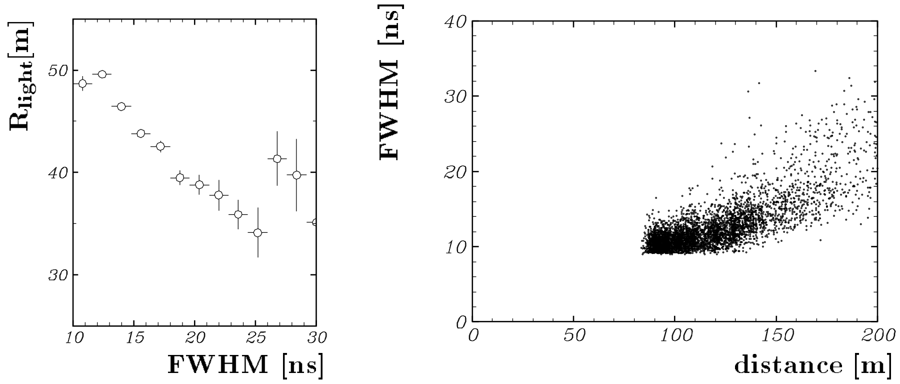

Figure 2: *(a) Measured correlation between the shape R_L of the lateral Cerenkov light distribution and the width (FWHM) of the arrival time distribution (at 150 m). (b) The measured width (FWHM) as a function of the distance to the shower axis as measured by a single counter.*

6 SUMMARY

A correlation of two parameters sensitive to the height of the shower maximum, namely the parameter R_L describing the lateral shape of the Cerenkovlight and the FWHM of the arrival time distribution has been shown in the data of the HEGRA experiment. An analysis is going on, using new methods for the energy determination [1] in order to infer the elemental composition from the measured arrival time distribution.

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