Composition and Energy Measurement with a New Method Applied to the HEGRA Data in the Energy Range of the Knee

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Abstract

With the integrating Cerenkov light measurement of the AIROBICC array at the HEGRA experiment the longitudinal development of extended air showers can be inferred. Using the combined information of the AIROBICC and scintillator arrays a new method is presented which allows the reconstruction of the energy of the primary hadron without knowledge of the hadron species. Simultaneously this new method determines also the mass of the primary hadron. In this way the HEGRA experiment allows to measure the elemental composition as well as the energy spectrum without the systematic uncertainties of other procedures for energies above 100 TeV. The method is described and a first application to data is presented.

1 INTRODUCTION

Due to the low flux of cosmic rays above an energy of several hundreds of TeV satellites and airborne detectors which measure the primary particles directly can not be used any more. The much larger sensitive area of ground based arrays allows to continue the flux measurement of cosmic rays to energies six orders of magnitude higher than the direct experiments, but one has to derive the properties of the primary particle from the measurement of the extensive air shower indirectly. As large fluctuations between individual showers dominate systematic differences of EAS induced by light and heavy nuclei one has to find methods that allow to reconstruct the shower development in the atmosphere. At energies around 1 PeV the elemental composition of cosmic rays has not been measured up to now although this is of great importance for the understanding of the origin and acceleration mechanism of charged cosmic rays. The so called "knee" may therefore reflect a real change in the energy spectrum, a changing elemental composition or a combination of both effects.

This paper describes a new method to derive the elemental composition and the energy spectrum for energies above 100 TeV from measurement of Cerenkov light and particle density at ground level using the HEGRA experiment.

2 THE EXPERIMENT

The experiment HEGRA is a multi component EAS detector system described in detail elsewhere [1]. At a height of 2200 m a.s.l. it covers an area of $180 \cdot 180\,\mathrm{m}^2$. Here only the scintillator array of 219 huts with a grid spacing of 15 m and a denser part near the center and the so called AIROBICC array of 49 open photomultipliers measuring the integrated Cerenkov light of air showers on a grid with 30 m spacing are

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used. The event reconstruction starts with the determination of the shower core from the scintillator data. With this core the airshower direction is fitted twice using the AIROBICC and scintillator time informations. The measured particle density in the plane perpendicular to the shower axis is fitted by the NKG formula. The Cerenkov light density can be very well described by an exponential $\rho_C(r) = A \cdot \exp(-r/R_L)$ in the interval $20\,m < r < 100\,m$ from the shower core.

3 SIMULATION

EAS in the energy range from 100 TeV to 5 PeV were simulated using the code CORSIKA 4.01 [2]. The events were passed through a detector simulation and reconstructed with the same program as for real data. Showers induced by primary proton, α, oxygen and iron nuclei were calculated. Each event was used 20 times to simulate different core positions inside the experiment and impact points outside, which nevertheless fire sufficient huts of the arrays to fulfill the trigger conditions.

4 ENERGY AND MASS RECONSTRUCTION

In this section a method to reconstruct energy and mass of the primary nuclei is described which is based on the measurement of the slope parameter of the Cerenkov light density R_L (defined above) and the integral of the fitted NKG function N_e. These parameters are the most robust from the four quantities calculated in the lateral fits, but also the intensity of the Cerenkov light and the shower "age" may be used to distinguish different primaries (see section 6).

It was found from MC studies that R_L is determined only by the distance of the shower maximum from the detector (measured in units of g/cm^2) [4]. Independently of the type of the primary nucleus this relation is valid for zenith angles up to 30°, where the efficiency of AIROBICC starts to decrease drastically. An elemental composition can be derived indirectly from the measured R_L distributions [5]. In the present paper, using R_L and N_e, first the energy reconstruction and afterwards the mass reconstruction will be discussed.

Energy reconstruction: The measurement of R_L allows to fix the position of the shower maximum with an accuracy of approximately $35\,g/cm^2$ including all experimental uncertainties (mainly core reconstruction and measurement of Cerenkov light intensity). MC simulations show that if the distance to the maximum is known (e.g. from R_L or the method described in [6]) N_e is proportional to the average energy E_{em} deposited as electromagnetic energy (energy of all π^0 mesons) by a hadronic shower of total energy E. The penetration depth of a shower into the atmosphere until the maximum is reached (reconstructed from R_L and the zenith angle Θ) only depends on the energy per nucleon E/A. With the measured electromagnetic energy E_{em} and the energy per nucleon E/A the total energy E can now be inferred using the correlation of E_{em}/E with E/A from ref. [7] which is reproduced by the CORSIKA simulations. The results of this method applied to MC data are shown in figure 1A. Systematic uncertainties in the energy reconstruction are around 10%. The resolution for E is approximately 30%, whereas 11% for 1 PeV protons could be reached without experimental uncertainties. It should be stressed that no assumption on mass composition is needed.

Mass reconstruction: From the determination of E and E/A the number of nucleons A can now be calculated. Figure 1B shows results for simulated p and iron

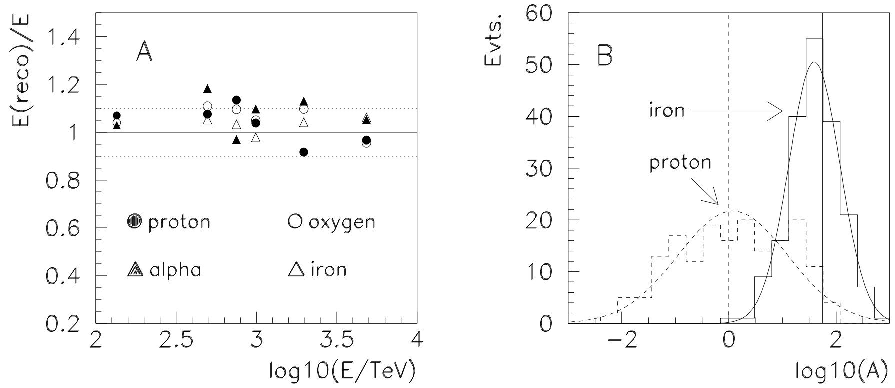

Figure 1: A: Comparison of reconstructed and generated energy for different primary energies and nuclei.
B: Reconstructed nucleon number for simulated protons and iron nuclei with energies around 1 PeV.

induced showers. A clear separation of proton and iron nuclei can be seen both in position and width. For primary protons the widths is dominated by the natural fluctuations in the position of the shower maximum, for iron nuclei the experimental resolution determines the width.

5 APPLICATION TO DATA

To apply the presented method to data one has to select a clean event sample as badly reconstructed showers may fake heavy primary nuclei for example. Showers with cores outside the sensitive detector area can be rejected by calculating the mean distance of the registered particles from the reconstructed shower core [8] and by comparing the two shower directions as reconstructed with the scintillator and AIROBICC arrays. Nights with bad seeing conditions are rejected by a method similar to [10]. The event selection does not bias any composition measurement. To simplify experimental corrections only events with zenith angles below 15° are taken into account.

The measured energy spectrum can be fitted by a function $\mathrm{N(E)} = \mathrm{a} \cdot \mathrm{E}^{-\gamma}$ and shows a change in the slope parameter of $\Delta\gamma = 0.4 \pm 0.2$ at an energy around 1 PeV. This is compatible with results obtained earlier [9].

The reconstructed number of nucleons is shown in figure 2 for the energy range from 500 TeV to 1000 TeV. The line shows a fit with a light, medium and heavy component using parametrizations of the CORSIKA simulations. Heavy nuclei constitute a considerable fraction of the primary particles. More detailed results and the extension to higher energies demand a careful study of saturation effects of the detectors which are currently underway.

6 FUTURE IMPROVEMENTS

The slope parameter of the lateral particle density ("age") as well as the amplitude of the Cerenkov light distribution have not been used in the previous discussion. They offer additional information on particle separation, but this has not been applied to data up to now. In contrast to the method presented in section 4, which only uses the longitudinal development of the showers, additional separation possibilities originate in different lateral shower developments. For a fixed total energy E the lateral spread of a shower increases with increasing nucleon number A as the typical transverse momentum in hadronic interactions stays roughly constant with energy per nucleon, but the longitudinal momentum of the nucleons drop inversely to A. Therefore less Cerenkov light is concentrated below a distance of 100 m from the shower core and the shower age is larger for heavier than for light nuclei.

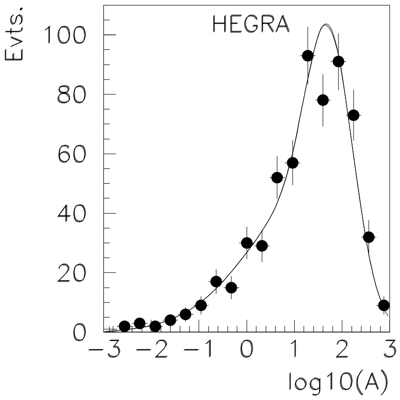

Figure 2: Reconstructed nucleon number A for energies between 500 and 1000 TeV and a preliminary fit to the data.

An energy determination for hadrons (see ref. [11] or [12] for a phenomenological approach) and a composition analysis corresponding to the method shown in section 4 can also be done with a "stand alone" AIROBICC type array, but a photon hadron separation requires the comparison to a scintillator array.

7 CONCLUSION

A method has been presented for EAS with energies above 100 TeV which allows to reconstruct (a) the primary energy without using any assumptions on elemental composition and (b) the mass of the primary nuclei without any assumptions on the energy spectrum. The experimental technique is mainly based on the measurement of the Cerenkov light by an array of open photomultipliers as realized with AIROBICC in the HEGRA experiment. A first application to data shows a change in the spectral index of the cosmic ray spectrum around an energy of 1 PeV of $\Delta\gamma = 0.4 \pm 0.2$ and the existence of a heavy component in the cosmic rays. More detailed results with higher statistics will be available soon.

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