The Energy Spectrum of Charged Cosmic Rays between 10^{14} eV and 10^{16} eV determined with the HEGRA Arrays

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Abstract

The HEGRA scintillator and Čerenkov light counters (AIROBICC) allow to determine the energy and coarse chemical composition of charged cosmic rays in the energy range between 10^{14} eV and 10^{16} eV. The measured quantities at ground level can be used to estimate the primary energy either by a primary mass dependent or independent method. Here we present and compare the energy spectra obtained with both methods.

1 Introduction

In general the energy spectrum of charged cosmic rays is well described by a power law over several decades of energy before and after the so called knee, where the slope changes. The study of the specific shape of the energy spectrum as well as the estimation of the chemical composition (OG.1.2.09 / Röhring et al., 1999) are of importance for the understanding of the origin and the propagation of the charged cosmic rays.

The energy spectrum obtained from the data of the HEGRA experiment presented here is determined from a measurement of the electromagnetic (*em*) part of an extended air shower (EAS) initiated by a primary cosmic ray particle. Monte Carlo (MC) based studies with the CORSIKA program package (Knapp et al., 1998) show that both, the density of Čerenkov photons L_{90} at 90 meter distance from the shower core and the number of particles $N_{e,max}$ at the shower maximum position are good estimators for the energy of the *em* part of an EAS. The primary energy is then obtained from the electromagnetic one by using a primary mass dependent (Arqueros et al., 1999) as well as an independent method (Lindner, 1998). In this contribution we concentrate on the estimator $N_{e,max}$ and compare the results obtained with these methods. With respect to recently published results (Arqueros et al., 1999) the statistics of the data set was increased by 30%.

2 The Experimental Setup and Event Reconstruction

The HEGRA experiment is located on the Canary Island La Palma at a height of 2200 meters above sea level. For the analysis presented here the matrix of 243 scintillator counters and the AIROBICC array of 49 open photomultipliers (wide angle Čerenkov counters (Karle et al., 1995)) placed on an area of $180 \cdot 180$ m^2 were used. The measured particle density in the scintillator counters is fitted by the NKG formula. Two parameters are derived, the shower size N_s and the age parameter. Due to the lead coverage of the scintillator huts the true shower size N_e is not observed. As the simulation of the lead coverage is included in the Monte Carlo N_s can be used for the analysis. The lateral Čerenkov light density distribution can be well described by an exponential function of the distance r to the shower core between 20 m and 100 m: $L(r) = L_0 \cdot \exp(r \cdot slope)$. The shape parameter $slope$ is inferred from this fit and allows to determine the height d_{max} of the shower maximum and thus the penetration depth in a primary particle independent way.

To ensure a good quality of the data several cuts on the obtained parameters are introduced. The comparison of parameters (core position, direction, etc.) determined independently with the scintillator counters and the AIROBICC array allows to tag badly reconstructed events. The data set used for this analysis was recorded between July 1995 and October 1997. Only periods without technical problems and with good

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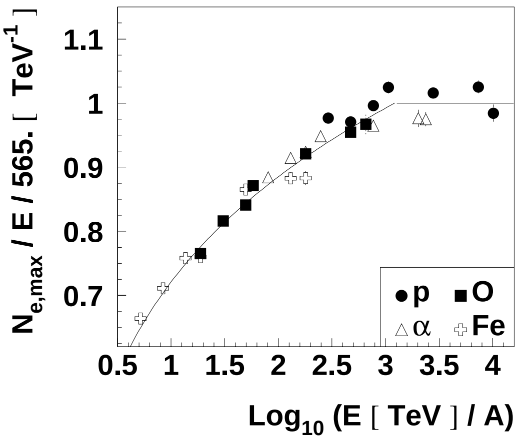

Figure 1: *The fraction of the electromagnetic energy (~ $N_{e,max}$) as a function of the energy per nucleon E/A for different primary particles.*

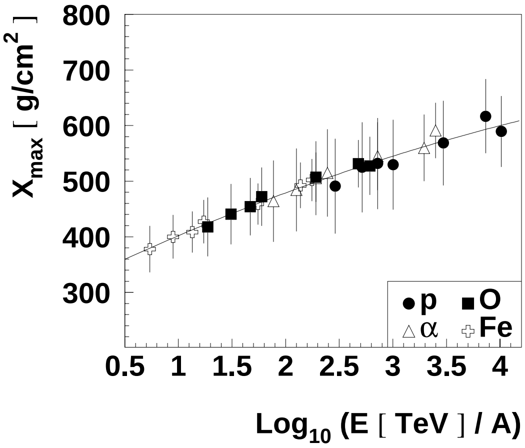

Figure 2: *The correlation between the depth of the shower maximum X_{max} and E/A. The vertical lines indicate the rms width of the depth distributions. The line shows a fit to the points.*

weather conditions were taken into account. The data set comprises a total ontime of 271 hours, corresponding to 225 000 events which fulfill the cuts (e.g. zenith angle $\Theta < 15°$), resp. 83 000 events above 300 TeV.

3 Monte Carlo Simulations

EAS events were simulated using the CORSIKA code (5.20) with the QGSJET/GHEISHA option. Complex nuclei were treated with the "complete fragmentation" ansatz. Proton, helium, oxygen and iron induced showers were generated in two samples with discrete energies between 300 TeV and 10 PeV (4400 independent showers) and continously distributed in energy between 50 TeV and 13 PeV (7720 showers) with zenith angles of $6°$ and $12°$. Each event was used 10 times with core positions inside and outside the HEGRA area to take into account the detector related fluctuations of observables and to check the event selection criteria.

4 The Energy Reconstruction Methods

Several methods were developed to reconstruct the energy of cosmic ray primary particles from the HEGRA data ((Arqueros et al., 1999), (Cortina et al., 1997), (Lindner, 1998)). In this analysis we concentrate on results using the number of particles $N_{e,max}$ at the position of the shower maximum, whereby $N_{e,max}$ is obtained in a primary mass independent way from the number of particles N_s at ground level and the $slope$ parameter of the Čerenkov light density distribution. In order to obtain the primary energy from the electromagnetic energy, primary mass dependent and independent methods will be applied and compared in the following. In order to obtain the differential flux spectra the finite energy resolution is taken into account by correction factors obtained from the MC simulations.

4.1 Primary Energy from Mass Dependent Methods The total primary energy can be directly reconstructed from the *em* one under the assumption that all primary particles are proton or iron nuclei. As these extreme assumptions lead to a bias on the determined cosmic ray flux, correction factors have to be calculated from the MC set using the measured mass composition (Arqueros et al., 1999). In the MC simulations also assumptions concerning the true energy spectrum have to be introduced to calculate these correction factors. The factors used in this work are derived with a MC generated differential energy spectrum described by two power laws with a knee position at 4.0 PeV and a spectral index of -2.68 below and -3.18 above the knee. By varying these parameters within reasonable limits it has been verified that the influence of this choice is negligible compared to the uncertainty of the correction factors due to the limited MC statistics. Finally the factors were fitted as a function of energy to obtain a smooth correction function. The methods starting with the extreme assumptions will be denoted with $E(N_s)_p$ and $E(N_s)_{fe}$ as in (Arqueros et al., 1999).

4.2 Primary Energy from a Mass Independent Method To reconstruct the energy independently of the primary particle type (following (Lindner, 1998)) an energy per nucleon dependent correction is introduced which is related to the penetration depth. As illustrated in Fig. 1 MC simulations show that the fraction of the primary energy which goes into the *em* cascade ($\sim N_{e,max}$) depends on the energy per nucleon E/A.

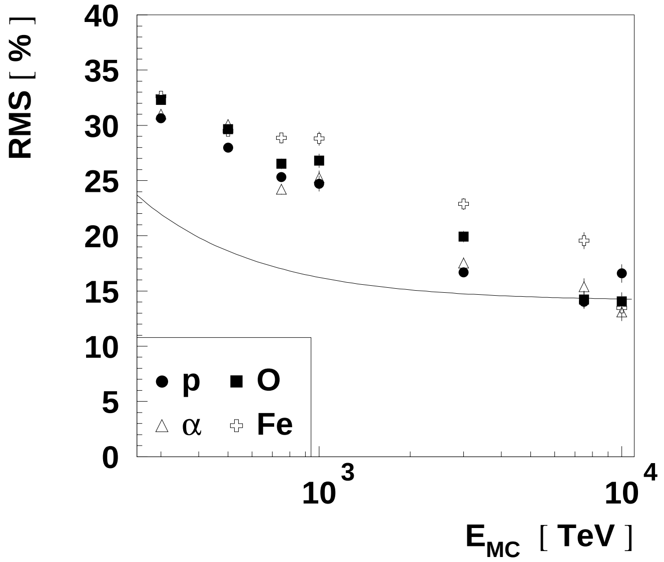

Figure 3: *The energy resolution (rms) as a function of the MC generated energy. The symbols indicate the resolution inferred with the method $E(N_s)$ for different primary particles. The line correspond to the energy resolution for the primary dependent method $E(N_s)_p$ (Arqueros et al., 1999).*

To determine E/A first the distance d_{max} between the detector and the position of the shower maximum is reconstructed independently of the primary particle type. The depth X_{max} of the shower maximum position in the atmosphere can be calculated using d_{max} and the zenith angle Θ of the incident particle. As can be seen in Fig. 2 the measured X_{max} can be used to estimate the energy per nucleon E/A.

Systematic effects on the reconstructed energy due to the energy dependence of the shape of the longitudinal shower development — as described in (Lindner, 1998) — are found to be less than 4 % and are neglected in this analysis. The primary independent method will be denoted with $E(N_s)$.

The main advantage of the primary independent method is that no assumption concerning the mass of the incident particle is necessary. However, the introduction of the energy per nucleon dependent correction results in a worse energy resolution compared to the primary dependent methods $E(N_s)_p$ and $E(N_s)_{fe}$. The energy resolution (the rms value of the distribution of the ratio of reconstructed to generated energy) of the primary independent method $E(N_s)$ varies from 32 % to 15 % in the considered energy range (Fig. 3). Up to energies of 2 PeV the energy resolution of $E(N_s)$ is 10 % worse compared to the primary dependent methods $E(N_s)_p$ and $E(N_s)_{fe}$. The good energy resolution of the primary dependent methods is achieved at the expense of systematic uncertainties due to the necessary correction of the composition bias. Nevertheless, the comparison of the results of these methods allows to test their reliability and to determine systematic errors.

5 Results: The Differential Energy Spectrum

Fig. 4 presents the differential energy spectrum derived with the three energy reconstruction methods described in section 4. All three methods show agreement in the general shape and the absolute flux at 300 TeV within the systematic errors. The spectra are fitted between 300 TeV and 10 PeV with two power laws connected at the position of the knee and the integral of the fit function fixed to the number of detected events. The obtained three fit parameters, the spectral indices γ_1 and γ_2 before and

Method	γ_1	γ_2	E_{Knee} [PeV]	$\chi^2_{d.o.f.}$
$E(N_s)$	$-2.67^{+0.03}_{-0.03}$	$-3.33^{+0.33}_{-0.41}$	$3.4^{+1.3}_{-0.7}$	2.0
$E(N_s)_p$	$-2.64^{+0.06}_{-0.07}$	$-3.27^{+0.49}_{-0.73}$	$3.0^{+2.3}_{-1.2}$	8.5
$E(N_s)_{fe}$	$-2.69^{+0.04}_{-0.06}$	$-3.27^{+0.49}_{-0.71}$	$3.0^{+3.1}_{-1.2}$	4.7

Table 1: *Comparison of the fit results: the spectral indices γ_1, γ_2 and the energy of the knee position (statistical errors only).*

after the position of the knee and the position itself are listed in table 1 with the χ^2 per degree of freedom ($\chi^2_{d.o.f.}$). The $\chi^2_{d.o.f.}$ values of the two primary dependent methods $E(N_s)_p$ and $E(N_s)_{fe}$ are rather bad, illustrating the fact that in both spectra some fine structures at energies below the knee appear. In contrast, the shape of the spectrum of the primary independent method $E(N_s)$ is smooth and the applied fit results in a rather acceptable $\chi^2_{d.o.f.}$ of 2.0. Despite the difficulty to describe all three spectra with one function, the fitted parameters agree. With respect to the results published in (Arqueros et al., 1999) the statistical error of the knee position for the primary dependent methods is decreased by a factor of ≈ 2. This decrease is due to a a knee position found at lower energies, a stronger change of the spectral indices and the increased data statistics.

The comparison of the results of three different energy reconstruction methods using the same observables demonstrates that small structures may appear in some reconstructed differential energy spectra but not in others.

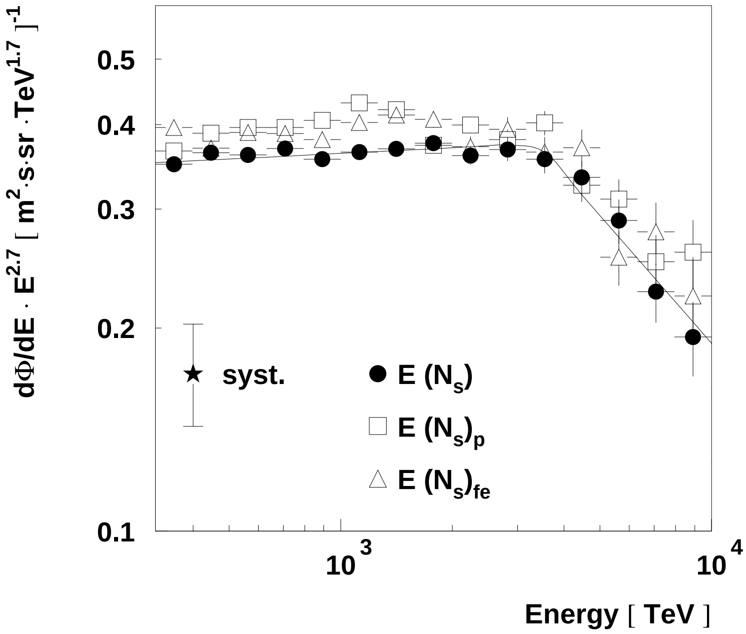

Figure 4: *The differential energy spectrum derived with 3 different methods. The line indicates a fit to the primary mass independent $E(N_s)$ spectrum. The star denotes the systematic error due to the uncertainty of the energy scale.*

6 Summary and Outlook

Three different methods were presented to reconstruct the energy of cosmic ray primary particles from data of the HEGRA scintillator counters and the AIROBICC array. The spectral indices and the knee position obtained with these methods are in agreement within the statistical errors. For the primary independent method $E(N_s)$ the spectral indices are $\gamma_1 = -2.67^{+0.03}_{-0.03}$ and $\gamma_2 = -3.33^{+0.33}_{-0.41}$ and the knee position is found to be $3.4^{+1.3}_{-0.7}$ PeV (statistical errors only). Investigations concerning the application of primary independent energy reconstruction methods using the Čerenkov light density L_{90} are under way.

7 Acknowledgments

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