The absolute CR-flux from 50 TeV to 15 PeV

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Abstract

The all particle energy spectrum at energies $>$ 50 TeV is measured using the lateral distributions of electrons, muons and Cherenkov photons. The data are from the HEGRA airshower array at ORM, La Palma. The energy spectrum is obtained using a regularised unfolding of the data on the basis of the Monte Carlo code CORSIKA. Different model inputs allow an estimate of systematic uncertainties. The position of the knee is determined as well as coarse information on the chemical composition.

1 Introduction

The energy spectrum and chemical composition of cosmic rays below and above the ‘knee‘ remains an area of intensive experimental activities. Up to about 100 TeV the results of direct experiments from detectors carried by satellites and balloons above the earth atmosphere provide a rather detailed and accurate picture of primary cosmic rays. At higher energies information on cosmic rays are entirely from ground based airshower arrays. An up to date and comprehensive overview of the results achieved so far can be found in Biermann et al. (1999).

2 HEGRA data

The HEGRA array on La Palma, Canary Islands (Karle et al., 1995) (Krawczynski et al., 1996) (Rhode et al., 1996) combines observations of Cherenkov photons, the e, γ component and muons of individual showers, to provide rather accurate energy reconstruction of the primary particles. Furthermore, the development of the CORSIKA air shower code (Heck et al., 1998) allows very detailed simulations of the shower development and in particular, to study the influence of different physical models on measured quantities. We describe here the results of an analysis of HEGRA array data, taken between October 1994 and April 1995, when the different components of the array had acceptable performance. 39 runs with $3 \cdot 10^4$ - $1.7 \cdot 10^5$ events triggered have been selected with appropriate weather condition for optimal observation for Cherenkov light using the AIROBICC array of HEGRA. About $5 \cdot 10^6$ events with zenith angle $\leq 30^0$ have been used for analysis. Furthermore 123 runs, mostly during day time when Cherenkov observation is not available, with good performance of the Geigertower and szintillator arrays have been selected for this analysis. This data sample contains $4 \cdot 10^7$ events with zenith angle $\leq 30^0$. Trigger thresholds taken at the 50 % efficiency point are 50 TeV (protons) and 110 TeV (iron) for the szintillator array with $\geq$ 14 stations required and 40 TeV (protons) and 100 TeV (iron) for the AIROBICC array at $\geq$ 6 stations. These values have been determined from CORSIKA simulations and have been found to depend (slightly) on the physics input of the Monte Carlo programs.

3 Analysis

In the analysis of the data we used an unfolding procedure based on ‘RUN‘ developed by V. Blobel at DESY (Blobel, 1984) and now widely used in various versions with all purpose storage ring detectors like e.g. H1 at HERA. The basic idea is to unfold from measured quantities $G(\vec{y})$ all distorting influences $A(x, \vec{y})$, resulting the experimental procedure, to obtain the true physical variable f(x) by solving the integral equation

$$G(\vec{y}) = \int A(x, \vec{y}) \cdot f(x) dx \quad (1)$$

The key issue here is an adequate handling of the distribution of the fluctuations which is based on complete modelling of the experimental conditions by Monte Carlo. With CORSIKA a suitable code has become available and based on it unfolding becomes possible in high energy cosmic ray physics.
Directly determined experimental quantities are N_e, the effective number of electrons determined from fitting a NKG function to the szintillator information and N_γ the number of Cherenkov photons obtained from AIROBICC information and the number of muons N_μ from a fit to the Geigertower information on the basis of the Greisen-parametrisation. As a qualitative result we find in all these quantities an indication of spectral break in the size distribution. For N_e-distributions we see a shift of the break to lower values of N_e with increasing zenith angle, θ, up to $1/\cos(\theta) = 1.6$. The real position of the break, the 'knee', is to be determined by converting the measured quantities N_e, N_μ, N_γ to a shower energy variable. We find from Monte Carlo studies the product of quantities $\log(N_e \cdot r_l)$ and $\log(N_\mu \cdot r_l)$ (with r_l the light radius from Cherenkov observations) to show very little dependences on the nature of the primary particle and a well behaved energy resolution of $\Delta\log(E_0)/\log(E_0)$ of about 30%.

4 Results on the energy spectrum

The all particle energy spectra for the 39 individual runs with N_e, N_μ and r_l well determined have been determined in 5 energy bins from 50 TeV - 15 PeV. This choise of energy bins matches approximately the energy resolution obtainable from our data, further subdivision in energy can therefore not provide more real physical information. The energy spectra of the individual runs have been fitted using the first 4 energy bins to a simple power law

$$d\Phi/dE = \Phi_0(E/100TeV)^{-\gamma} \tag{2}$$

to obtain the normalisation Φ_0 and the spectral index γ. The values found are compatible with Gaussian distributions with mean values $\gamma = 2.63 \pm 0.02$ and $\Phi_o = 0.85 \pm 0.05 \cdot 10^{-6}$ [$m^2 \cdot s \cdot sr \cdot TeV$]$^{-1}$. From a variation of physical input parameters of the CORSIKA Monte Carlo used to unfold the data we estimate an additional systematic uncertainty of $\pm$ 0.09 for γ, and +0.24/-0.06 for the normalisation Φ_0. As developments in understanding the physical input of CORSIKA proceeds, we expect that systematic uncertainties can be further reduced.
The data points above 4 PeV are found to be systematically below the extrapolation using the fit to the 4 lower energy points. This is an 8 σ effect for all 39 runs taken together. To determine more precisely the position of the knee the 39 runs are grouped into 4 samples with slightly shifted energy bins and then applying the unfolding procedure. The 4 energy spectra obtained have been fitted by two power laws resulting in spectral indices $\gamma_1 = 2.63 \pm 0.02 \pm 0.09$ (syst.) below the knee at $2.5 \pm 0.5 \pm 0.5$ (syst.) PeV and $\gamma_2 = 3.03 \pm 0.10 \pm 0.10$ (syst.) above the knee. Systematic uncertainties (syst.) have been estimated from using different physical model inputs to CORSIKA. Statistical errors have a dominating contribution in particular for the high energy points from very limited Monte Carlo statistics. This limitation is a consequence of the need to model the shower development in air simultanously for the particles and the Cherenkov light which at energies above a few PeV becomes very time consuming.

These results of this analysis are in substantial agreement with those results in Röhring, A. et al. 1999a and Röhring, A. et al 1999b, follwing a different analysis method.

5 Chemical composition

The RUN unfolding procedure allows for an analysis method with signal events on a general background. This feature can be used to divide the data into two groups chosen as light elements (H + He) and heavy elements (C - Fe). The analysis runs with one group as signal and the second as background and the reverse. From this procedure the energy spectra of light and heavy elements have been extracted again in 5 energy bins from 50 TeV to 15 PeV. A power law (2) has been fitted to the data obtained resulting for the light element group (H + He) in $\gamma = 2.72 \pm 0.07$ and $\Phi_0 = 0.52 \pm 0.03 \cdot 10^{-6}$ [$m^2 \cdot s \cdot sr \cdot TeV$]$^{-1}$ and for the heavy group (C - Fe), $\gamma = 2.57 \pm 0.11$ and $\Phi_0 = 0.30 \pm 0.03 \cdot 10^{-6}$ [$m^2 \cdot s \cdot sr \cdot TeV$]$^{-1}$. This indicates a trend to heavier nuclei at the knee. A more definite conclusion would be possible on the basis of the present data sample, once improvements of the Monte Carlo codes become available and significantly more showers can be simulated at energies beyond a few PeV.

Acknowledgements

The support of the German Ministry for Research and Technology BMBF and of the Spanish Research Council CYCIT is grateful acknowledged. We thank the Instituto Astrofísico de Canarias (IAC) for the use of the HEGRA site at the Roque de los Muchachos and its facilities at La Palma.

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