Estimation of the Chemical Composition of Charged Cosmic Rays between 10^{14} eV and 10^{16} eV with the HEGRA Arrays

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Abstract

Data of the HEGRA scintillator and AIROBICC arrays are used to determine the coarse chemical composition of charged cosmic rays in the energy range between 10^{14} eV and 10^{16} eV. Especially the wide angle integrating Čerenkov counters (AIROBICC) allow to measure the penetration depth of the shower maximum, a parameter which is correlated with the energy per nucleon. By analyzing the distribution of penetration depths in six energy intervals the coarse chemical composition of cosmic rays can be derived. The results are achieved using a primary mass independent method to determine the energy.

1 Introduction

The shape of the energy spectrum and the chemical composition of charged cosmic rays especially in the energy range of the knee are of great interest for the understanding of the acceleration and propagation mechanisms of the charged cosmic rays. The determination of the energy and mass of primary cosmic ray particles above 100 TeV suffers however from the difficulty that due to the low flux cosmic rays can only be measured indirectly via extended air showers (EAS) with large ground based installations. The observables accessible with the HEGRA arrays are related to the electromagnetic part of an EAS. Information about the primary mass is obtained essentially from the penetration depth which is defined by the position in the atmosphere where the number of particles of the EAS reaches its maximum. By examination of the distributions of penetration depths in intervals of reconstructed energy a coarse information concerning the chemical composition of cosmic rays can be obtained.

For the energy reconstruction method the reader is referred to a second contribution (HE.2.2.01 / Röhring et al., 1999) where the method as well as the obtained differential energy spectrum will be presented. For both contributions, this one and HE.2.2.01, the same data set was used. Results on the chemical composition using other energy reconstruction methods have been shown elsewhere (Arqueros et al., 1999).

2 The Observables and the Method

In this section we present the mass and energy sensitive observables relevant for this analysis and describe briefly the method to estimate the chemical composition.

Basically the lateral density distributions of the particle and the Čerenkov light shower front of an EAS are analyzed. The NKG formula is fitted to the particle density distribution measured with the scintillator counters to obtain the shower size N_s at ground level and the so called age parameter. The lateral Čerenkov light density distribution is fitted with an exponential function between 20 m and 100 m distance to the shower core, yielding the Čerenkov light density L_{90} at 90 m core distance and the $slope$ parameter.

The crucial quantity used for the chemical composition is the penetration depth. Because the lateral Čerenkov light density distribution depends on the longitudinal shower development the distance d_{max} between the detector and the shower maximum position can be determined with the $slope$ parameter using: $d_{max} = (672 + 20529 \cdot slope)$ g/cm^2. Simple geometrical considerations then allow to calculate the penetration depth X_{max} in the atmosphere.

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Monte Carlo (MC) simulations show that for a fixed energy the mean and the rms values of the X_{max} distributions depend on the incident primary particle type. For example at 300 TeV proton showers penetrate about 120 $\mathrm{g/cm}^2$ deeper in the atmosphere than showers initiated by iron nuclei. Because proton showers are subject to larger fluctuations the corresponding rms values of the depth distributions are about 100 $\mathrm{g/cm}^2$ for protons and about 54 $\mathrm{g/cm}^2$ for iron nuclei.

For the estimation of the chemical composition the X_{max} distributions are analyzed in six energy intervals between 316 TeV and 10 PeV, according to $\Delta\log(E/\mathrm{TeV}) = 0.25$. The energy of the cosmic ray particles is reconstructed in a primary independent way using basically N_s and $slope$ (Lindner, 1998). Following the description in (Röhring et al., 1999) this method is denoted with $E(N_s)$.

To compare the X_{max} distributions of the data set with MC based expectations, extended air showers of proton, helium, oxygen and iron nuclei were simulated using the CORSIKA program package (version 5.20) (Knapp et al., 1998) with the QGSJET/GHEISHA hadronic interaction model. Altogether 7720 independent showers randomly distributed between 50 TeV and 13 PeV were simulated. The MC showers are reconstructed using the same code applied to the data and are finally weighted to simulate the observed energy spectrum according to $dN/dE \sim E^{-2.68}$.

	number of events			
$E(N_s)$ [PeV]	data	MC	$\chi^2_{d.o.f.}$	$\frac{p+\alpha}{all}$
0.31-0.56	47622.	1914.	1.93	$0.52^{+0.23}_{-0.14}$
0.56-1.	18788.	1920.	3.46	$0.46^{+0.18}_{-0.13}$
1.-1.78	6892.	875.	2.35	$0.36^{+0.18}_{-0.13}$
1.78-3.16	2437.	301.	3.76	$0.62^{+0.24}_{-0.44}$
3.16-5.62	852.	268.	0.90	$0.24^{+0.26}_{-0.18}$
5.62-10.	257.	162.	0.82	$0.48^{+0.48}_{-0.39}$

Table 1: *The results of the one parameter fit of the MC to the data X_{max} distributions and the number of events in the data and the MC sample used for each energy interval. The errors are statistical only*.

The chemical composition is estimated by a χ^2 fit in which a superposition of the X_{max} distributions expected for different elements is fitted to the experimental X_{max} distribution. For the fitting procedure the MC showers are combined into two mass groups: proton (40%) and helium (60%) are added for the light mass and oxygen (65%) and iron nuclei (35%) for the heavy mass group (extrapolated from direct data (Wiebel-Sooth & Biermann, 1998)). For each interval of reconstructed energy the X_{max} values of the data and the MC set are filled into histograms with 50 bins from 0 $\mathrm{g/cm}^2$ to 1000 $\mathrm{g/cm}^2$. The fraction w of the light mass group is determined by minimization of:

$$\chi^2(w) = \sum_{i=1}^{50} \frac{(d_i - (w \cdot mc_i^l + (1-w) \cdot mc_i^h))^2}{(\sigma(d_i))^2 + (w \cdot \sigma(mc_i^l))^2 + ((1-w) \cdot \sigma(mc_i^h))^2}, \tag{1}$$

with d_i, mc_i^l and mc_i^h denoting the content of the i-th bin of the data, the light and the heavy mass group distribution and σ the corresponding statistical errors. The total number of events in the MC was normalized to the number of data events and bins with no entries in the data or MC distributions were omitted.

3 Results

In Fig. 1 the data X_{max} distributions of the six energy intervals are plotted. Also shown are the results of the fitting procedure, the fitted contributions of the light and the heavy mass group. Fig. 1 demonstrates that the data X_{max} distributions are described rather well by the MC. In the first energy interval a fraction of the light mass group of 52^{+23}_{-14} % is determined in agreement with recently published results (Arqueros et al., 1999). Table 1 summarizes the fit results for all six energy intervals. Due to the low number of events in the MC as well as in the data set the results at and above the position of the knee suffer from large statistical uncertainties. Systematic uncertainties in the mass composition analysis are mainly related to the determination of the $slope$ parameter. If contributions of the detector and atmospheric effects are considered the systematic error on $slope$ amounts to 5 %. It is possible to take this systematic error into account by fitting a second parameter $X_{max,shift}$, a global shift in X_{max}. However, due to the low statistics in the last three energy bins several combinations of parameters $X_{max,shift}$ and fraction w of light particles can be fitted with acceptable $\chi^2_{d.o.f.}$ values and therefore no general trend for a shift in X_{max} can be claimed.

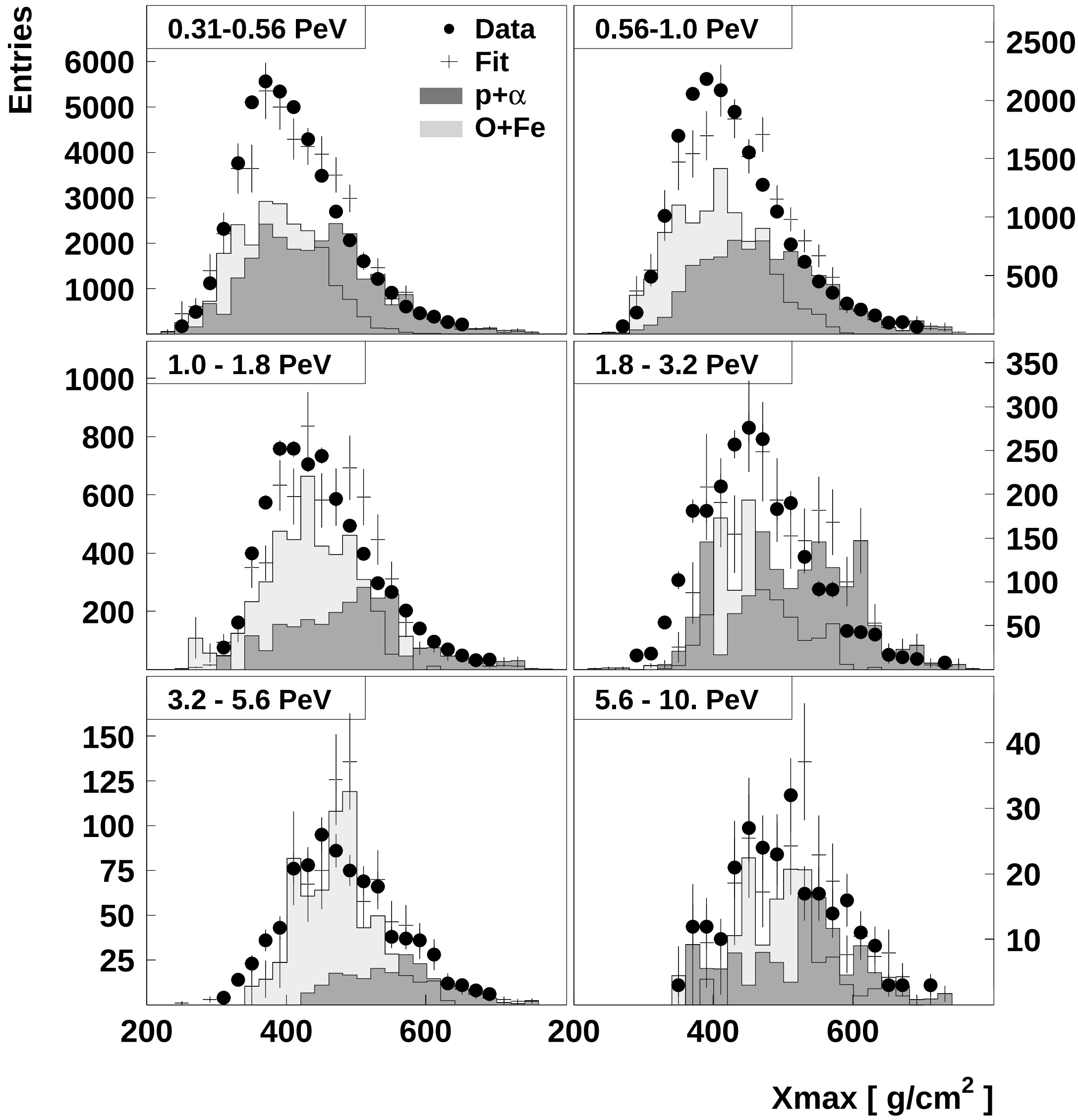

Figure 1: *The data X_{max} distributions (black dots) and the fitted contribution of the light (dark shaded) and the heavy mass group (bright shaded) for the six intervals of reconstructed energy. The crosses denote the sum of the two mass groups with statistical errors.*

In Fig. 2 the mean penetration depth X_{max} is plotted versus the reconstructed energy $E(N_s)$. As both parameters, $E(N_s)$ as well as X_{max} depend on $slope$ their correlation has to be taken into account to avoid biased results. In this analysis correction factors for the mean value of the measured X_{max} were calculated from the MC set. An alternative way to treat these correlations is to apply an unfolding procedure as described in (Wittek & Kornmayer, 1999).

The systematic error of X_{max} includes the uncertainty of the correction factors as well as the uncertainty of the $slope$ parameter. Fig. 2 shows that in the considered energy range the mean X_{max} values of the data distributions are compatible with a mixed chemical composition. A drastic change in the mass composition with increasing energy is not observed. A fit of a straight line to the X_{max} values as a function of energy yields an elongation rate of (64.8 ± 0.7) g/cm^2 (statistical error only). The uncertainty of the elongation rate is dominated by the systematic error which has not been estimated at present.

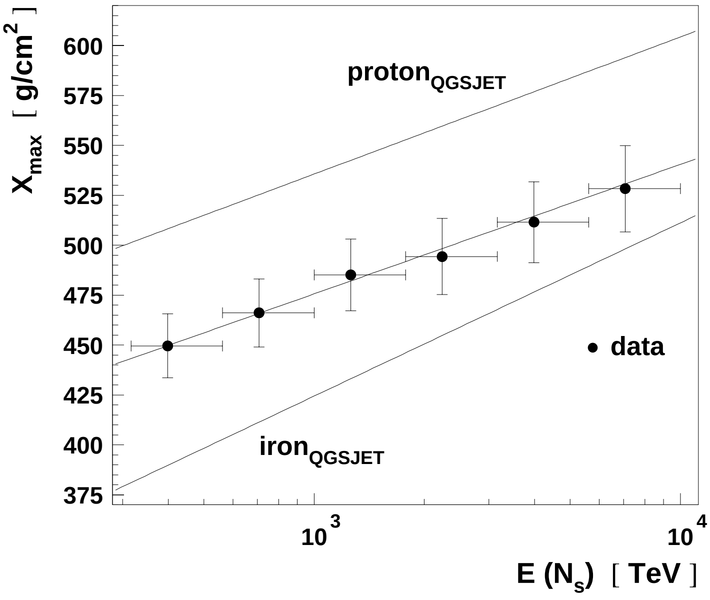

Figure 2: *The mean penetration depth as a function of energy. To obtain unbiased results (see text) the X_{max} values were multiplied with correction factors. The vertical lines indicate the combined statistical and systematic uncertainty. Also shown are the predictions for a chemical composition of pure proton or iron nuclei within the QGSJET model and the result of a fit to the data points with a straight line.*

4 Summary

The coarse chemical composition has been estimated in six energy intervals between 316 TeV and 10 PeV. The fraction of light particles ($p + \alpha$) was determined by a χ^2 fit of MC based penetration depth distributions to the data. The obtained fraction of light particles as well as the mean values of the penetration depth are compatible with a mixed chemical composition in the considered energy range. No drastic change in the mass composition with increasing energy is observed.

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