A study of the coarse chemical composition of cosmic radiation between 300 and 1000 TeV

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Abstract

An analysis of the chemical composition between 300 and 1000 TeV based on the fluctuation of the shower maximum using data from the AIROBICC and scintillator array of the HEGRA installation is presented. Within the errors the composition is in agreement with the low energy composition over the whole energy range.

The chemical composition beyond about 100 TeV will provide a decisive clue about cosmic-ray origin because nearly all current theories predict large changes in the composition which rising energy. Direct measurements in balloon and satellites are difficult in this energy range because of the small primary flux. A major effort is therefore underway at many places[1] to develop a methology to reliably derive the chemical composition from data gathered with ground based installations with their very large collecting areas. Here we present a method based on the measurement of the lateral distribution atmospheric Čerenkov light and the electron number N_e and apply it to a small subsample of the data collected with the AIROBICC[2] and scintillator array of the HEGRA installation[3] at La Palma. The analysis extends over an energy range with just overlaps with the last datapoint from a large balloon experiment[4]. The basic idea of our analysis is to derive the chemical composition from the fluctuations of the height of the shower maximum. It is well known [1] that proton induced showers have a fluctuation which is about a factor of 3 larger than that of iron induced showers. This is a large factor and one would think it should be easy to discriminate these two components. Moreover, especially for high energies, the size of the fluctuation is determined

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mainly by the primary interaction cross section which can be reliably calculated. Two requirements have made progress difficult however:

• the instrumental resolution in determining the shower height should be not much larger than fluctuation of showers induced by heavy nuclei. This condition is fulfilled for the AIROBICC detector which is capable to determine the height of maximum with a precision of about half a radiation length[2], which is comparable to the fluctuation of iron induced showers.

• The showers should be sorted in primary energy intervals before the composition is determined. If they are sorted e.g. according to N_e or Čerenkov light density within about 90 m of the core, the selected shower sample will be heavily biased in favor of proton induced showers, which complicates the ensuing analysis considerably. Different methods were developed in the HEGRA collaboration to determine the primary energy independent of chemical composition [5] and a similar procedure was used here.

Our analysis is based on the 'Madrid library' of 2400 Monte Carlo (MC) showers based on the Corsika program V3.02 including a detailed detector simulation[6]. This library extends to 1 PeV, this sets our upper energy limit. The data set consists of 3 nights of data from February/March 1993 selected according to special criteria of atmospheric quality (they are discussed in Ref.[7]). A fourth night was analyzed independently to check the stability of the results. Data from the zenith angle interval 0-15 ^{o} were analyzed and compared with MC showers of 10 ^{o} zenith angle.

The following quality cuts were applied to both the MC and real data:
distance of shower core from edge of array 25 m; χ^2 of scintillator cone timing fit < 4; 'banana cut' in N_s vs number of fired huts plane[8]; $\log_{10} N_s < 4.5$; $0.6 <$ NKG shower age < 1.7; number of fired scintillator huts >40.

It was checked that no MC showers with a primary energy > 300 TeV were removed by these cuts. The lateral Čerenkov light distribution as determined from a fit to the MC data was fitted to a single exponential between 10 and 90 m core distance. The decay constant λ (inverse of the 'light radius') was plotted against the ratio $P=N_s/$(primary Energy in TeV) for the energy intervals 300 - 448, 448 - 669 and 669 - 1000 TeV for the components p,O,Fe (N_s is an indirect measure of N_e [6]. λ is directly proportional to the height of the shower maximum[8]. A linear fit was found to be satisfactory to describe the resulting dependencies. These fits were then used to determined P from the λ for a given shower in the data. Then, with the measured N_s the primary energy is determined.

In order to remove a chemistry dependent energy bias as much as possible, a rough preselection of showers into the groups p,O,Fe was performed. Showers induced by heavy primaries have on the average a somewhat smaller 'complement angle' (defined as $(\pi-\alpha)/2$, where α is the opening angle of the timing cone[2]) for a given λ than lighter primaries. The complement angles ('cslopes')

were plotted against λ for the three components and the resulting dependencies were again represented by linear fits. A shower in the data was first classified as belonging to one of the three components by finding the fit curve next to it in the cslope vs. λ diagram and then its P value was determined with the appropriate P vs. λ curve. This procedure ('NSC' for N_s-Slope- Cslope) was checked with the MC data, by creating 1 dimensional histograms of the estimated/true energy for the three components. The resulting disributions had a mean(RMS) of 1.15(0.57), 1.04(0.38) and 0.89(0.28) for p,O,Fe respectively, so the energies are determined by the NSC procedure with about 40 % precision and only a small chemistry dependent bias.
The MC data were sorted into the energy intervals according to their estimated energies. In each interval a histogram of the λ distribution for each component was plotted. Because the MC data are distributed roughly equally over the energy range >300 TeV each shower was weighted according to (estimated energy/true energy)$^{-2.7}$ in order to simulate the effect of the steeply falling flux spectrum in the real data. The assumption of this spectrum for all components was later confirmed via self consistency. It was found that Gaussians provide a reasonable fit to the λ histograms. The fit results (mean and standard deviation) were then used to fit the real data with the normalization constant as a free parameter. Because the energy dependence of the fitted curves is small over the energy range considered here, mean values for the position and standard deviation were used for all three energy interval in order to improve MC statistics. The fitted constants together with their statistical error as determined from the covariance matrix, provide an estimate of the abundancy of a given component. Systematic errors are in the mean λ from uncertainties in the light density calibration (lcal), and Corsika input physics for nucleon-nucleon interactions (mcal, not treated here). Detector uncertainties in the standard deviation of the λ are negligible for protons, the error is dominated by the statitical fit error to the MC distributions (mswidth) For heavy primaries MC uncertainties according to the fragmentation behaviour of the nuclei dominate detector uncertainties. This uncertainty has been discussed recently by Kalmykov and Ostapchenko and Schatz et al.[9] with results that seem to agree quite well. As an estimate for the MC uncertainty (mfwidth) we take the difference of estimated fit results with realistic fragmentation as given in Kalmykov and Ostapchenko and the ones obtained with total fragmentation (as assumed in Corsika V3.02). The results of our analysis are summarized in table 1. Fig.1-3 shows the λ distributions used to derive the abundances. It was not possible to discriminate oxygen and iron. For a comparison with other results (table 2) we added their helium and proton abundance as a comparison with our fitted proton abundances. Our results are in good agreement with the JACEE low energy abundancies. We find no evidence for a change in chemical composition up to 1 PeV within our errors.

Figure 1: λ distributions with fitted abundances (dash:p,dotted:O,dot-dash:Fe) for the three energy intervals

	300 - 669 TeV	448 - 669 TeV	669 - 1000 TeV
proton	56(4,9,3,-8)	48(5 ,12,2,-14)	59(4,7,2,-6)
heavy	44(6)	52(9)	41(6)

Table 1: Fraction in % of the cosmic radiation in the given energy interval fitted to protons and oxygen and iron(heavy) respectively. The first number in brackets is the statistical error, the following the systematical lcal,mswidth and mfwidth error respectively (see text).

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	[4] 45 TeV,[10] 100 TeV	[4] 370 TeV	[11] 1000 TeV
p+He	65(10),56	37(13)	36
helium	30(6),36	23(10)	30

Table 2: Results of a direct experiment[4] with total error, a recent compilation[10] and a recent theoretical prediction [11].