OG 6.1.24

CHANGES OF THE COSMIC-RAY MASS COMPOSITION AT THE KNEE

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ABSTRACT

The Cosmic Ray Tracking (CRT) detectors are tracking detectors of 2.5 m^2 area with excellent muon identification. Ten CRT detectors have been operated at the HEGRA air-shower array on La Palma, Canary Islands. Data taken together with CRT detectors and the HEGRA array have been analysed to investigate changes of the cosmic-ray mass composition at the 'knee' of the cosmic-ray flux spectrum. The analysis is based on the angular distributions of particles in air showers. HEGRA data provided the core location, the shower size and direction and CRT data the particle track information. Results of the muon radial angle analysis can be easily expressed in terms of $\langle \ln A \rangle$ of primary cosmic rays. In the lower part of the covered energy range (from about 10^{14} to 10^{15} eV) we have considerable overlap with direct composition measurements by the JACEE collaboration and find compatible results in the observed rise of $\langle \ln A \rangle$. Between 10^{15} and 10^{16} eV energy we find no or at most a slow further rise of $\langle \ln A \rangle$. Simple cosmic-ray composition models are compared with our composition results and with flux measurements by other experiments.

INTRODUCTION

The Cosmic Ray Tracking detectors were originally built as prototypes for a proposed low-threshold air-shower array (Heintze et al., 1989) and were designed to have good angular resolution and a very good muon/electron discrimination. With the ten CRT detectors installed at the HEGRA array (Aharonian and Heinzelmann, 1997; Lindner, 1997), it turned out that even with this test installation the CRT detectors together with the HEGRA array could be used to measure the cosmic ray mass composition.

Although the total sensitive area of 25 m^2 of the ten CRT detectors is too small for mass measurements on an event-by-event basis, these detectors are very well suited for measuring average properties together with an air-shower array like HEGRA. These properties include the muon/electron ratio and the angles of muons and electrons in air showers. For the analysis presented here, we wanted a very good control of detector effects over almost 3 orders of magnitude in shower size. Because detector effects are particularly well understood for muons and can be checked in the actual data, we used the muon angular distributions for this analysis. Results for electrons are consistent with those for muons but are restricted to smaller shower sizes and are less sensitive to the fraction of heavy elements.

EXPERIMENTAL SETUP

The CRT detectors (Bernlöhr et al., 1996a) consist of two circular drift chambers of the TPC type of 2.5 m^2 area each and a 10 cm thick iron plate between them, all in a gas-tight container. Each drift chamber has six proportional sense wires of which four have additional readout of segmented cathodes (*pads*). Wires and pads are readout by a 40 MHz Flash-ADC system to a local VME computer system at each detector station. Detector control and online track reconstruction is done by the same computer. The achieved spatial resolution of the CRT detectors (Bernlöhr et al., 1996b) is about 1 mm both in drift direction (from the measured drift times) and in wire direction (by combining charge-division and cathode pads), corresponding to an angular resolution of about 0.4° for energetic particles. For low-energy electrons there is significant scattering in the container walls.

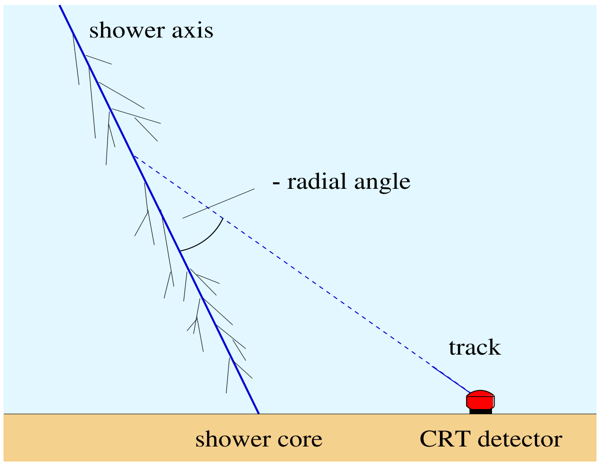

Fig. 1: Definition of radial angles between shower axis and muon tracks (in a vertical plane through detector and shower core).

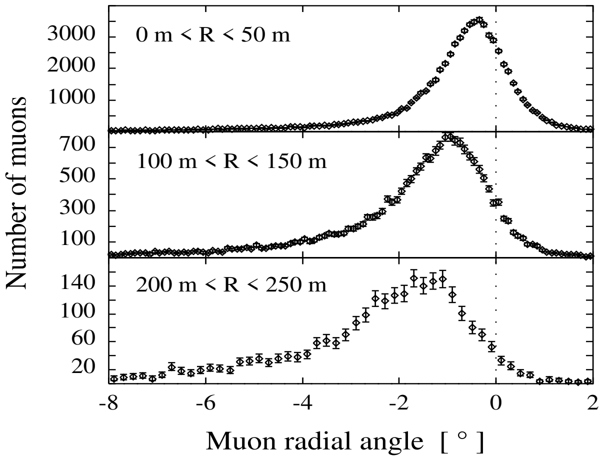

Fig. 2: Histograms of muon radial angles for three intervals of core distance R and HEGRA shower size between 24000 and 67000.

Muons are identified as pairs of corresponding tracks in upper and lower drift chamber, matching both in direction and their intersect in the iron plate. The muon detection efficiency as a function of momentum is given by multiple scattering and energy loss in the iron plate. With the usual cut at an angle of less than 2.5° between the two tracks in both projections, the CRT detectors are 50% efficient at 1 GeV and almost 100% efficient above 2 GeV (see Bernlöhr et al. (1996b) for details). By the angular cuts and by requiring that the lower muon track should be isolated, we achieve a very good rejection of punch-through electrons. The drift direction in one chamber is parallel to the wires in the other and vice versa. By taking the muon direction as the average in both chambers, each projection of it has the same angular resolution.

Ten CRT detectors were installed at the site of the HEGRA array in 1993 and 1994, initially for detector tests. Eight detectors are inside the HEGRA array area and two detectors are outside to measure tracks at core distances of up to 280 m (for showers with cores well inside the HEGRA area). For part of the time the CRT detectors were operated with a trigger from the HEGRA array and the corresponding array data were kindly provided by the HEGRA collaboration. This analysis presented here is based on a part of that data, which corresponds to a total life time of 42 days in 1994 and 1995.

For the analysis we used the core position, shower direction and shower size as reconstructed from the HEGRA scintillator array data. Data from the AIROBICC array (available for about 10% of the events) have only been used to check and correct for systematic effects in the shower direction from scintillator data.

ANALYSIS

For the analysis the angle of muon tracks with respect to the shower axis is used in two perpendicular projections: the *radial angle* (see Figure 1 for definition, Figure 2 for measured distributions) and the *tangential angle*. The radial angle is sensitive to the longitudinal shower development. Note that we define it as negative for particles coming from the axis. The tangential angle, on the other hand, has an intrinsic distribution which is, by definition, symmetric around zero and is narrow compared to the experimental resolution. It is used to derive the combined angular resolution of CRT muons and HEGRA showers. Because CRT preamplifiers are saturated when a detector is hit by more than about 20 particles and muon identification is hampered still earlier, the analysis is restricted to large core distances (80–280 m) where muons can be reconstructed even in large showers.

The method underlying our analysis is described in detail by Bernlöhr (1996). Median values of the muon radial angles are computed for 10 m bins of the horizontal distance from the shower core.

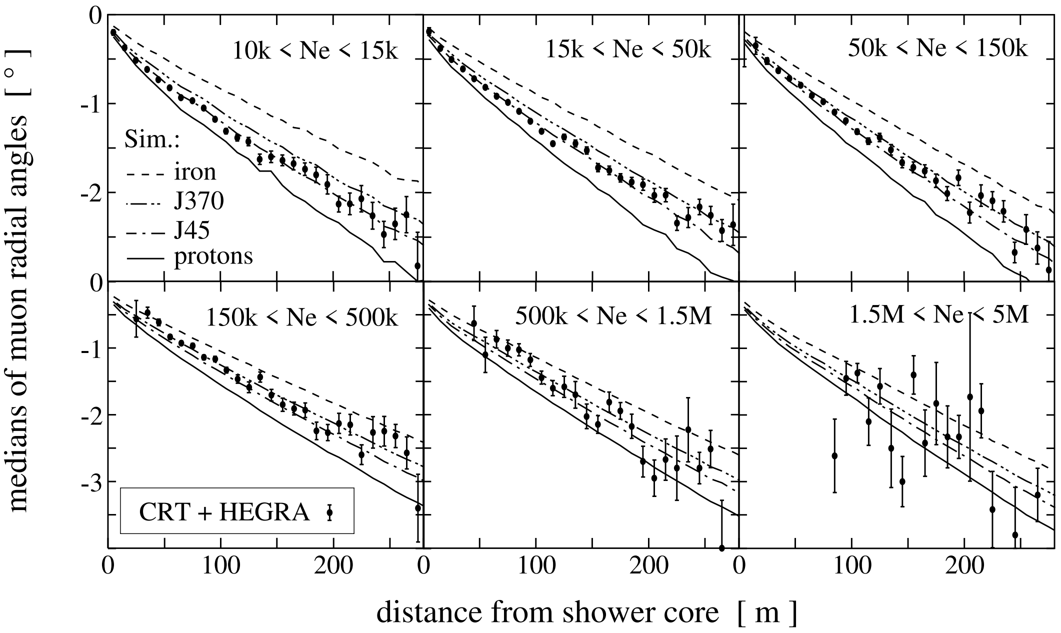

Fig. 3: Measured median muon radial angles and simulations for protons, mixed compositions J45 and J370 (see text), and for iron.

Corresponding simulations have been carried out with the CORSIKA shower simulation program and a detector simulation. The later includes the CRT detection efficiency of various particle types (muons, electrons, gammas, protons, pions) as muon tracks and the corresponding angular resolution as functions of momentum and angle of incidence. The detector simulation also includes the HEGRA resolutions of shower direction, core location and shower size and takes the relation between the HEGRA measured shower size N_h and the corresponding size N_e in CORSIKA into account. Simulations have been carried out for five types of primaries: protons, helium, nitrogen (for the CNO group), magnesium (for Ne–S), and iron (for $Z > 17$). The CORSIKA (versions 4.068 and 4.50) simulations were done with several interaction models to have an estimate of possible systematic errors from the models.

The parameter Λ tells where the data on average are between the simulated proton and iron curves of median muon radial angles as functions of core distance. Λ can be calculated as

$$\Lambda = \frac{1}{\sum w_i} \sum_i w_i \frac{\langle \alpha_i \rangle - \langle \alpha_{i,\mathrm{p}} \rangle}{\langle \alpha_{i,\mathrm{Fe}} \rangle - \langle \alpha_{i,\mathrm{p}} \rangle} \quad ,$$

with $\langle \alpha_i \rangle$ as the measured muon radial angle in core distance interval i, $\langle \alpha_{i,\mathrm{p}} \rangle$ and $\langle \alpha_{i,\mathrm{Fe}} \rangle$ the corresponding simulations for protons and iron nuclei, and w_i weights obtained from the statistical errors of $\langle \alpha_i \rangle$. Λ can also be obtained from a least-squares fit, which is equivalent to the weighted average, or from a maximum likelihood fit taking into account the asymmetric and non-Gaussian errors of the median radial angles in case of small statistics. This deviation from Gaussian distributions was only relevant in our largest shower size interval ($1.5 \cdot 10^6 < N_e < 5 \cdot 10^6$).

Simulations with pure compositions (p, He, N, Mg, and Fe) as well as with various mixed composition show that Λ is, to a good approximation, proportional to the average logarithm of mass numbers, $\langle \ln A \rangle$. Therefore, we use $\langle \ln \tilde{A} \rangle = \Lambda \ln 56$ as an approximation to $\langle \ln A \rangle$.

RESULTS

Figure 3 shows measured and simulated median muon radial angles as functions of core distance for six intervals of shower size N_e. The mixed compositions J45 and J370 correspond to JACEE measurements (Asakimori et al., 1993) above 45 and above 370 TeV and are assumed to be energy-independent. The average energies corresponding to the shower size intervals are summarized in Table 1.

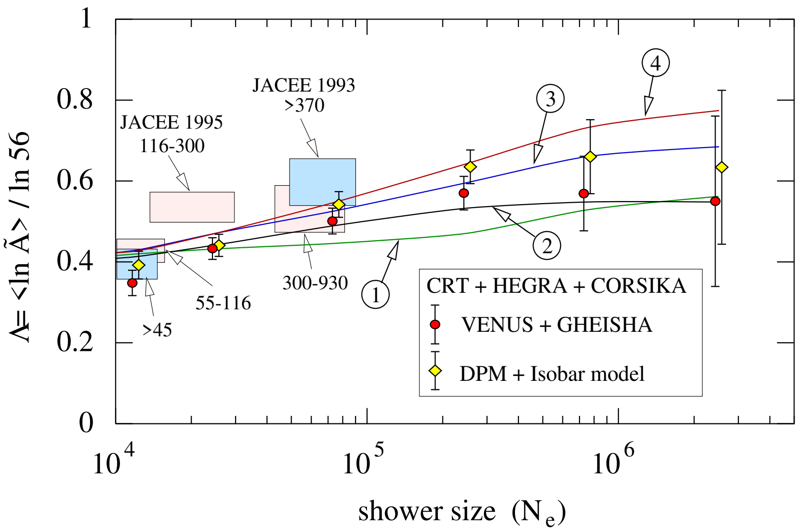

Fig. 4: Λ from CRT/HEGRA data compared with direct measurements and models (see text for details).

Table 1: Average shower energies

shower size N_e	$\langle E \rangle$ in PeV for protons	iron
$(1.0–1.5) \cdot 10^4$	0.057	0.19
$(1.5–5.0) \cdot 10^4$	0.105	0.32
$(0.5–1.5) \cdot 10^5$	0.29	0.78
$(1.5–5.0) \cdot 10^5$	0.77	1.8
$(0.5–1.5) \cdot 10^6$	2.3	4.7
$(1.5–5.0) \cdot 10^6$	5.7	10.5

The resulting Λ values are presented in Figure 4 for two sets of CORSIKA interaction models and compared to corresponding values for directly measured compositions (Asakimori et al., 1993; Asakimori et al., 1995), with good agreement, as well as to four models. In addition to the Λ error bars shown there are systematic errors of 0.08 common to all measurements.

The models are normalized to JACEE measurements between 55 and 116 TeV. Models 1 and 2 correspond to a sudden change either in acceleration efficiency or propagation at a fixed rigidity pc/Ze for nuclei of momentum p and charge number Z. They have identical spectral indices for all elements below and above the respective knee rigidity. Models 3 and 4 are extrapolations of JACEE measured compositions (Asakimori et al., 1995). Model 1: slope -2.57 below a knee rigidity of 500 TV and -3.04 above, model 2: slope -2.7 below 100 TV and -3.05 above, model 3: slope changes to -3.01 above 200 TV, model 4: slope steepens by 0.6 at 200 TeV.

These models have also been compared with flux measurements of several experiments around the knee region (not shown here). Models 1 and 3 are in very good agreement with the shape of the flux spectrum while model 4 is in reasonable agreement. The knee in model 2, however, is at a much too low energy to be in agreement with the flux measurements. We did not find any simple model like 1 and 2 which is in agreement with both our composition results and the available flux spectra but an extrapolation of JACEE measurements like model 3 is in good agreement.

ACKNOWLEDGEMENTS

We would like to thank the HEGRA collaboration for their support of the installation and operation of the CRT detectors on La Palma and for providing the array data used in our analysis. It is also a pleasure to thank the authors of the CORSIKA shower simulation program.

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