Muons in Extensive Air Showers and the Cosmic-Ray Composition near the Knee

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Abstract

With the Cosmic Ray Tracking (CRT) detectors and the HEGRA air shower array at La Palma the arrival directions of secondary particles in air showers have been measured. Muons with a momentum above about 1 GeV/c are distinguished from other types of particles. The arrival directions of muons with respect to the shower axis and also the electron directions and the muon-to-electron ratio as a function of the core distance are sensitive to the primary cosmic ray composition in the energy range 10^{14} eV to a few times 10^{15} eV. The measurement methods, simulations and preliminary results are presented.

1 Introduction

Direct measurements of the chemical composition of primary cosmic rays with balloon-borne or spacecraft experiments run out of statistics at energies near 100 TeV per particle [1, 2]. Indirect measurements with air shower experiments are not limited by statistics at these energies but rather by the shower fluctuations. These fluctuations are at least of the same order of magnitude as the average differences between the lightest and the heaviest cosmic-ray nuclei in any observable quantity. Air shower experiments are therefore more suitable to measure some sort of average composition by a statistical analysis of many events than to do an event-by-event classification. For a review of various methods applied by different experiments see [3]. The intention of the present paper is to present another method which seems very promising but has, to our knowledge, not been applied by previous experiments.

For the CRT project a test-array of 10 tracking detectors [4] has been installed at the site of the HEGRA experiment [5] on La Palma, Canary Islands, at an altitude of 2200 m a.s.l. This installation which was mainly intended for a performance evaluation of CRT detectors is successfully operating for two years now. For about half of that time the CRT test-array has been operated with a trigger from the HEGRA array. Processed HEGRA shower data have been kindly provided by the HEGRA collaboration and were combined offline with the CRT data.

Independent data of shower directions and core positions (from HEGRA) as well as tracks and types of shower particles (from CRT) are available. Because CRT detectors achieve a very good muon-electron discrimination, the angular distributions are measured separately for muons and electrons.

To separate the effects of scattering and experimental resolution from those due to the shower development, the angles are measured in two projections defined by the shower axis and the position of the detector that recorded a given track. The radial angle of a particle track with respect to the shower axis is the angle in the plane of the shower axis and the detector. By convention, a negative sign is used for the more frequent case of a particle flying away from the axis (see fig. 1). Measurements of the corresponding apparent height of origin of muons have already been done more than 20 years ago [6] but could not be interpreted in terms of the chemical composition at that time. In the orthogonal projection, the symmetric distribution of the tangential angle (also called transverse angle) accounts mainly for scattering processes in the atmosphere and the experimental resolution.

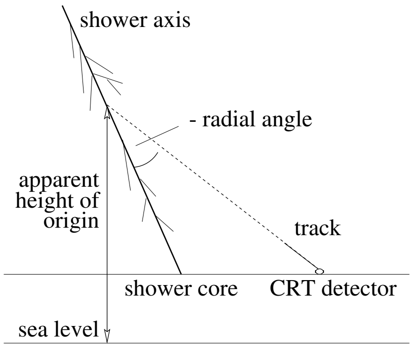

Figure 1: In the plane defined by the shower axis and the CRT detector position a radial angle of a particular track with respect to the shower axis can be measured as well as the apparent height of origin, assuming that the particle was produced on the shower axis. A negative radial angle is assigned to a track as shown. The tangential angle is measured in the orthogonal plane.

2 Composition-dependent parameters

The CRT detectors in the HEGRA array can measure the angular and lateral distributions of both ‘electrons’ and ‘muons’. Detailed simulations show that the ‘electron’ sample includes a 30% fraction of gammas converting in the detector container while the ‘muon’ sample includes a small admixture of pions and punch-through electrons near the shower core but little contamination at larger core distances. Among the angular distributions the tangential angles of both electrons and muons show no dependence on the type of primary in simulation calculations. Indeed, the tangential angle distribution of muons can be used to measure the combined angular resolution of CRT and HEGRA accurately as a function of the HEGRA shower size (see fig. 2).

The radial angle distribution shows a pronounced dependence on the composition, both for electrons and muons. For iron showers which, on average, develop earlier in the atmosphere than proton showers the radial angle distribution is more symmetric than for proton showers. This results in a less negative mean or median value of the

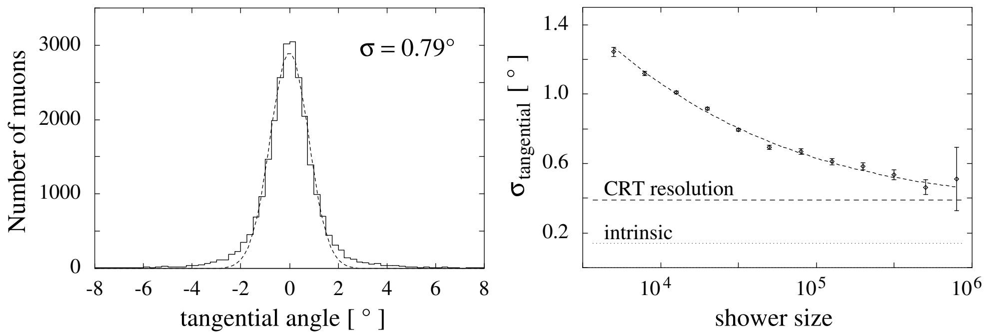

Figure 2: Left: Distribution of tangential angles of single CRT muon tracks with respect to the HEGRA shower axis, using showers of any size. The fitted resolution includes the experimental resolutions of CRT and HEGRA as well as the intrinsic width. Right: The resolution of the tangential angle improves with the HEGRA shower size. The CRT resolution of 0.4° for muon tracks is essentially independent of the shower size. The intrinsic width is small compared to the experimental resolution.

radial angle in any interval of the core distance. In alternative terms, secondary particles in showers of heavy primaries appear to originate higher in the atmosphere than secondaries in proton showers.

Average shower parameters obtained from the electron sample are for two reasons not very conclusive as far as the chemical composition of cosmic rays is concerned. Due to the soft spectrum of electrons and gammas in the showers not only a very accurate simulation of the air showers but also of the various detector components is required to know the parameters expected for different types of primaries. Furthermore, shower sizes at the altitude of the HEGRA array are much smaller for heavy primaries than for protons. This results in a severe trigger bias of the HEGRA array in favour of light primaries. Electron sample parameters of a composition with a modest contribution of heavy nuclei, therefore, are virtually indistinguishable from those of a pure proton composition. Indeed, the measured median of the electron radial angle as a function of core distance agrees quite well with detailed simulations of proton showers but not with iron showers [7].

Although the same trigger bias is also present in the muon sample, it is almost compensated by the larger number of muons produced by heavy primaries. For this reason, muon sample parameters are more sensitive to modest admixtures of medium to heavy primaries. In contrast to the electrons, the detection efficiency for muons is very easy to understand because it is mainly due to the multiple scattering in the 10 cm thick iron plate between the two drift chambers of a CRT detector. Muons are required to have an angle of less than 2.5° between the corresponding tracks in the upper and lower drift chambers. Therefore, CRT detectors are mainly sensitive to muons above about 1 GeV/c momentum.

Preliminary results obtained with a fraction of the CRT/HEGRA data set are presented in fig. 3. It should be noted that data beyond 130 m core distance are based on two CRT detectors outside the HEGRA array. The orientations of these two detectors with respect to the HEGRA reference frame have, so far, not been calibrated to better than 0.3°. Detectors inside the HEGRA array are calibrated to better than 0.05°. At core distances below 30–50 m the muon reconstruction is deteriorated in large showers due to detector saturation. Corresponding shower size thresholds are applied for measured as for simulated data. The median of the measured shower size corresponds to a primary energy of about 150 TeV for protons and about 300 TeV for iron nuclei. The measured resolution of CRT and HEGRA from fig. 2 has been used for the simulations. Systematic errors of the shower simulations (using CORSIKA version 4.068) are estimated to be of the order of 10–15% of the difference between protons and iron.

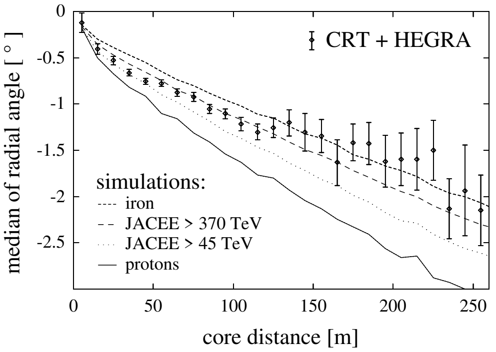

Figure 3: Measured median of muon radial angles with respect to the HEGRA shower axis as a function of the core distance. Error bars are statistical errors only. See text for systematic errors. The curves are simulations, for pure proton, pure iron, and chemical compositions as published for two energy ranges [1].

3 Conclusions

Measurements of particle tracks in air showers can be used to check models of the chemical composition of cosmic rays near the knee of the energy spectrum. Our preliminary results, in particular for the muon data, are in favour of a heavier composition than measured at TeV energies. It is consistent with the balloon experiments [1, 2]. Detailed tests with a larger data set and an improved calibration of the two CRT detectors outside the HEGRA array are in progress.

References

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