2.2 High-energy astrophysics

2.2.1 The CRT project

K. Bernlöhr, W. Hofmann, G. Leffers, M. Panter, U. Trunk, R. Zink

The Cosmic Ray Tracking (CRT) detectors are detectors for tracks of secondary particles in cosmic-ray or gamma-ray initiated air-showers. These detectors consist of two circular drift chambers of 2.5 m^2 area each and a 10 cm thick iron plate inbetween. Electrons and muons can be distinguished very well with CRT detectors. Ten detectors are operated at the HEGRA experiment on La Palma, Canary Islands (Spain), at an altitude of 2200 m. Performance evaluations have shown that CRT detectors meet or even exceed initial performance goals. The ten detectors at La Palma are now usually operated together with the HEGRA array.

The angular distributions of particles in air showers can be investigated very well with the combined data of CRT and HEGRA. The main purpose of these investigations is to look for changes of the cosmic-ray mass composition near the so-called knee in the cosmic-ray flux spectrum at energies of 10^{15}–10^{16} eV. First results show a slow increase in the average particle mass at energies just below the knee. With more data coming in, this combination of instruments will allow to study also the composition at energies above the knee.

2.2.1.1 Introduction

The earth is exposed to a steady stream of high-energy particles from outside the solar system, the cosmic rays. These are predominantly protons and completely ionized nuclei. Because such particles are diverted by the Galactic magnetic field and scattered on interstellar plasma waves, their arrival directions give no clues to the places of their origin or acceleration. The nature of the cosmic particle accelerators can, for this reason, be investigated by hardly any other means than looking for sources of high-energy γ-rays and by the composition of the cosmic rays.

The original aim of the CRT project was to install an experiment with almost 400 CRT detectors at a high-altitude site in order to look for sources of high-energy γ-rays [1, 2]. The CRT detectors consist of two circular drift chambers of 2.5 m^2 area each and a 10 cm thick iron plate inbetween as a muon filter.

Compared to conventional scintillator experiments such tracking detectors promise a much lower energy threshold for shower measurement and an improved angular resolution [3]. In combination with the potential to suppress hadronic air-showers initiated by protons and nuclei, a CRT experiment as proposed would achieve lower thresholds for γ-ray sources than any existing experiment – except the imaging Cherenkov telescopes. In contrast to CRT, such telescopes are restricted to observe single candidate sources during clear, moonless nights.

A total of 10 CRT detectors as developed in the CRT project [4] were installed at the site of the HEGRA experiment on La Palma [5] during 1993 and 1994 – mainly for evaluation of the detector performance. This evaluation has been essentially completed in the meantime. The initial expectations in the detector performance are met or even exceeded [6]. In parallel, studies concerning the relevant electronics were continued at Heidelberg.

In combination with the HEGRA experiment, in particular the scintillator array, the CRT detectors have found a new goal by investigating the mass composition of ultra-high-energy cosmic rays. This combination of instruments is particularly sensitive to changes in the composition from 10^{14} eV – where direct measurements from balloon experiments are available – to about 10^{16} eV or more, which is already above the knee in the flux spectrum.

2.2.1.2 Measurements at Heidelberg

There exist two different designs of preamplifiers for CRT detectors. Each of these designs has its advantages and its drawbacks compared to the other. Measurements with two detectors – each equipped with one type of preamplifiers – have been carried out in order to compare the performance of the two types. The measurements have been completed [7]. One of the detectors was equipped with charge-sensitive preamplifiers as used in the CRT detectors on La Palma. The other was equipped with current-sensitive VV49-II amplifiers and with pulse shapers adapted for these preamplifiers. Otherwise, identical readout systems with the 40 MHz Flash-ADC system developped at the MPIK were used. Coincidences of four scintillation counter triggered the CRT detectors mainly on events with a large number of tracks.

The charge-sensitive preamplifiers are in saturation after about 20 hits per wire and event, corresponding to more than 20 particles hitting a detector. The current-sensitive amplifiers do not show such a saturation but have, on the other hand, a larger noise. The larger noise results in a 15% worse spatial resolution by charge-division and a 45% worse resolution with the segmented cathode strips. Only in the resolution in drift direction there is no significant difference between the two preamplifier types.

The noise values expected from the designs of the two preamplifier types are consistent with the measured resolutions. The saturation of the charge-sensitive preamplifiers is also consistent with expectation. Despite their saturation but due to their superior resolution, the chargeßensitive preamplifiers will remain in use in the CRT detectors.

2.2.1.3 Measurements on La Palma

The ten CRT detectors at the site of the HEGRA experiment on La Palma were almost entirely used to take data with triggers from the HEGRA array during 1995. The data are mainly intended for investigation of the cosmic-ray composition. Additional measurements were carried out to calibrate the detector orientation with respect to the HEGRA array. A large spirit-level was used to measure the inclination of the detectors. In addition, the two detectors outside the HEGRA array were operated during several weeks with a special-purpose trigger-counter for vertical muons.

For the normal data aquisition, the track reconstruction is now done online and only track data but no raw or hit data are recorded. That reduced the amount of data substantially. No offline track reconstruction is necessary anymore. At the usual trigger rate of the HEGRA array (usually 8–12 Hz) there is no significant CPU dead-time introduced by the online reconstruction.

With the exception of certain calibration measurements, all data aquisition was controlled from Heidelberg via Internet, like in previous years. Changing the data-tape cartridges and some minor maintenance work was carried out by the HEGRA operators which is gratefully acknowledged.

The CRT detectors work without problems. Not even exchanging the counting gas (an argon-methane mixture 80:20) was necessary during 1995. CRT detectors again meet the goal that even a much larger CRT array could be operated with little on-site maintenance staff.

2.2.1.4 Shower reconstruction

The arrival direction of air showers can be reconstructed from track data of CRT detectors by a maximum-likelihood method [8]. Since the location of the shower core can usually not be reconstructed from data of the few CRT detectors, the core location is optionally taken from the HEGRA scintillator data. This reconstruction method was intended for an evaluation of the angular resolution for showers which can be achieved by the tracking detectors. The shower direction reconstructed from HEGRA scintillator data served as a reference.

The achieved resolution (see figure 1) is apparently somewhat inferior to previous expectations of a resolution of $(3°–4°)/\sqrt{n}$ [3] for a large CRT array (n being the number of tracks). However, this discrepancy is mainly due to the fact that for these tests only events with many tracks in each detector (typically 10–30 tracks together in six detectors) could be used. At these large numbers of tracks, the track reconstruction deteriorates substantially. In typical events recorded with a large CRT array, the average track density would be much lower. A resolution of about $4°/\sqrt{n}$ can be expected with the detectors in stainless-steel containers. With aluminium containers a slightly

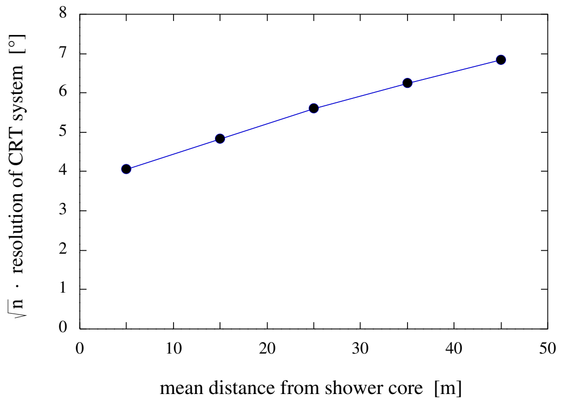

Figure 1: The angular resolution of the CRT system on La Palma multiplied by the square root of the number of tracks used for the fit, displayed as a function of the mean distance of tracks from the core.

better resolution could be expected due to less scattering of electrons in the container.

2.2.1.5 Investigation of the cosmic-ray composition

Most of the current investigations with CRT detectors concentrate on the search for changes in the cosmic-ray mass composition near the *knee*. The knee in the flux spectrum of cosmic rays between 10^{15} and 10^{16} eV is usually attributed to a change from a predominant contribution from supernova remnants below the knee to a second, yet unclear type of sources above the knee. Knowing by how much the composition changes in this energy range could give very important clues to the nature of the sources.

The procedure carried out with CRT is based on angular distributions of mainly muons but also electrons with respect to the shower axis, depending on the type of primary. The arrival direction of the particles is available from CRT data and the direction of the shower axis from the HEGRA scintillator array. In different core distance intervals the median value of the *radial angles* is computed. The radial angle is the angle between track and shower axis projeted onto the vertical plane defined by the core and CRT locations (see figure 2). This method is not suitable for telling the type of individual primaries but for evaluating *mean values* of the composition. In the case of muons, for example, the mean logarithm of the mass numbers A, $\langle \ln A \rangle$, can be obtained.

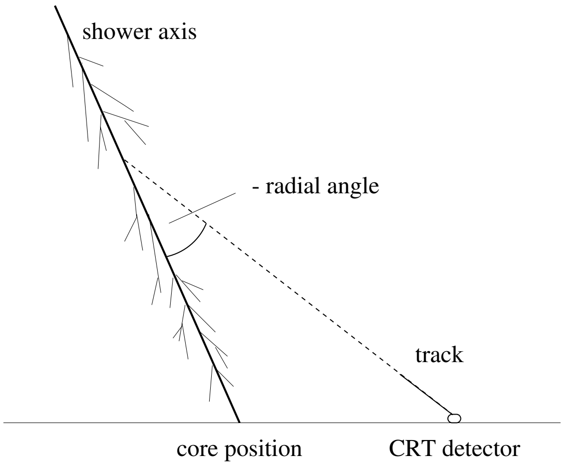

Figure 2: Definition of radial angles (negative for particles moving away from the shower axis as shown).

Like any other *indirect* method for measuring the composition – where only air showers but not the primaries are measured – this method depends on comparisons with simulations. In contrast to the majority of previous methods applied by other experiments, the radial-angle method using CRT and HEGRA data has two important advantages: First, the most important experimental effects are very well known or can be measured with the actual data and, second, results at energies below 10^{15} eV can be compared with results of direct measurements. A large number of minor experimental effects is parametrized from very detailed detector simulations [9] and included in the necessary simulations for this analysis. This method is very promising with respect to the control over systematic errors. Figure 3 shows the dependence of measured median values of muon radial angles compared to results of simulation calculations.

An analysis of a part of the data recorded so far [11] shows that the radial angle method is in good agreement with direct measurements at energies

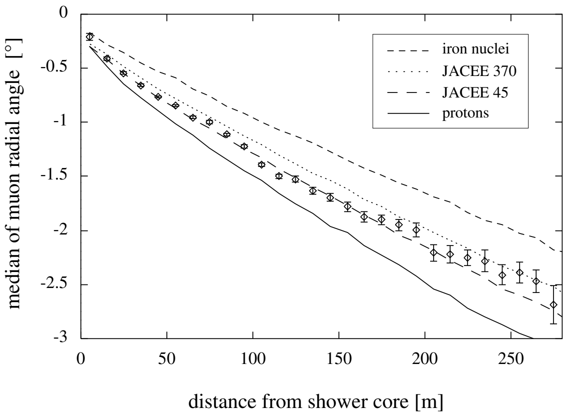

Figure 3: Median values of muon radial angles as a function of the distance from the shower core, compared to simulations for pure protons, pure iron nuclei, and mixed compositions like measured by JACEE [10].

up to a few 10^{14} eV, both for muon tracks (see figure 4) as well as for electron tracks.

We found an increasing fraction of heavy nuclei and a decreasing fraction of protons in the energy range from about 10^{14} to $5 \cdot 10^{15}$ eV. The amount of available data is still increasing and should be sufficient to measure $\langle \ln A \rangle$ up to energies above 10^{16} eV, which is well above the knee.

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[5] V. Fonseca et al. 1995, Proc. 24th International Cosmic Ray Conf., Rome, Vol. 1, p. 474

[6] K. Bernlöhr et al. 1996, Nucl. Instr. and Meth. A369, ... (Paper II)

[7] U. Trunk 1995, diploma thesis, Heidelberg

[8] G. Leffers 1995, Ph.D. thesis, Heidelberg

[9] R. Zink 1995, Ph.D. thesis, Heidelberg

[10] K. Asakimori et al. 1993, Proc. 23rd International Cosmic Ray Conf., Calgary, Vol. 2, p. 21 and p. 25

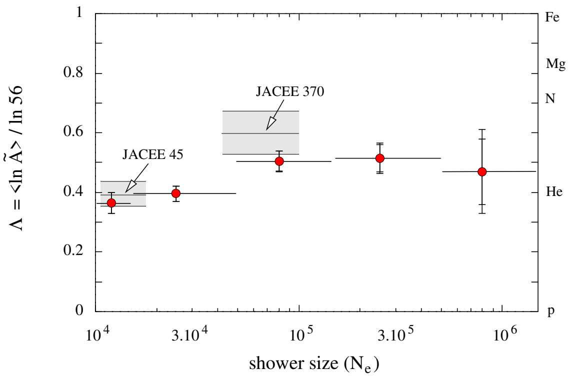

Figure 4: The parameter Λ (here for muons as a function of shower size) tells where measured median radial angles are, on average, between the expectations for pure protons ($\Lambda = 0$) and pure iron nuclei ($\Lambda = 1$). For comparison the values expected for directly measured compositions of the JACEE collaboration [10] are shown with corresponding statistical errors. The displayed range of shower sizes corresponds to energies of about 10^{14} to almost 10^{16} eV.

[11] K. Bernlöhr 1995, habilitation thesis, Heidelberg