SELECTED RESULTS FROM
GROUND-BASED COSMIC RAY AND
GAMMA-RAY EXPERIMENTS

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Abstract
Selected results from the HEGRA experiment on charged Cosmic Rays and on very high energy gamma-rays are presented. The MAGIC Telescope is presented as an outlook to the future of Gamma-Ray astronomy.

1 Introduction to Ground-Based Cosmic Ray Data
As a general rule the dynamic range of precision detectors is limited to roughly 2 to 3 orders of magnitude in energy. In case of the charged Cosmic Rays (CR) with an energy spectrum extending over more than 13 orders of magnitude, this necessitates a large number of different experimental setups in order to cover the full spectrum. Space-borne, i.e. direct, experiments, cover the spectrum from $\approx 10^7$ eV to $\approx 10^{15}$ eV/nucleon, and ground-based experiments operate above total energies of a few $10^{12}$ eV up to more than $10^{20}$ eV.

In the following we will concentrate on the ground-based measurements. Here various experiments which are sensitive in the energy region around $10^{15}$ eV consistently show a significant steepening of the all-particle spectrum around this energy. When studying the data more closely, however, the agreement between the experiments turns out to be not so good, i.e., differences well above the fluctuations given by the individual errors. This is shown in fig. 1 where the data on the 'knee' in the all-particle spectrum are collected. From these data one must conclude that the absolute position, the 'sharpness' of the knee, and also the absolute flux in this energy region are more uncertain than expected from the individual errors. Ground-based experiments use a detector, i.e. the atmosphere as absorber with some added readout elements, like scintillators, Cherenkov detectors, etc., which can only be calibrated in the laboratory to a very limited degree. The calibration therefore has to rely very

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heavily on MC simulations of the development of the extensive air showers and of the performance of the detectors. One possible reason for the deviations in the measured spectra might thus be the use of different Monte Carlo (MC) generators in the data analyses. This will be briefly discussed below for the most recent data.

2 The Energy Spectrum and the Chemical Composition

Currently the two experiments HEGRA [3], located within the Observatorio del Roque de los Muchachos on the Canary island La Palma, and KASCADE [4], located near Karlsruhe, Germany, are analysing their airshower data with respect to the all-particle spectrum and the chemical composition of the CR near the 'knee'. In the following we shall discuss some of the preliminary HEGRA results and compare to KASCADE where appropriate.

The HEGRA setup for the detection of CR with energies above $\approx 15$ TeV has 3 components: (i) 243 scintillator stations of 1 m$^2$ each distributed over 40,000 m$^2$, (ii) 77 AIROBICC Cherenkov detectors spread out over the same area, and (iii) 17 Geiger towers within the central 15,000 m$^2$. 

![Figure 1: The charged Cosmic Rays all-particle spectrum around the 'knee' as measured by a number of ground-based experiments (taken from [1]).](image)
2.1 The Reconstruction of Energy and Mass

The measured distribution of particle densities in the scintillator array is fitted to yield the shower size \( N_e \) at detector level and the correlated shower size at the maximum \( (X_{\text{max}}) \) of the shower development. The lateral Cherenkov light density, \( \rho_C(r) \), is analysed in the interval \( 7.5 < r < 100 \) m and can be described by an exponential

\[
\rho_C(r) = a \cdot \exp(r \cdot R_{\text{light}}),
\]

where the shape parameter, \( R_{\text{light}} \), is inversely proportional to the absolute penetration depth, \( X_{\text{max}} \), of the analysed shower. As MC investigation show, this proportionality is essentially independent of the mass, \( A \), of the incident primary particle. The achieved resolution for \( X_{\text{max}} \) varies between 1.0 and \( \approx 0.5 \) radiation lengths \( (X_0 = 36 \text{ g/cm}^2) \) for energies between 100 TeV and a few PeV. The reconstruction of the energy in two independent analyses relies either on a combination of \( N_e \) and \( R_{\text{light}} \), or on a combination of \( N_e, N_\mu \) (the corresponding muon shower size), and \( R_{\text{light}} \). In both cases an energy resolution of \( \approx 30\% \) is achieved. Using the CORSIKA simulation program \[3\] different hadronic interaction generators (i.e., VENUS, QGSJET, HDPM, DPMJET, SIBYLL) can be used. MC investigation have shown that the qualitative sensitivity for physics parameters and e.g. the energy resolution is independent of the hadronic interaction generator. The absolute energy scale, however, turns out to be dependent on the MC generator and the chemical composition.

2.2 The Energy Spectrum

Using the VENUS model within CORSIKA, HEGRA performed a regularized unfolding of the measured \( N_e \) distributions on a run-by-run basis (see [1] for details). The result of the unfolding is shown in fig. 2.

The spectral index of the all-particle spectrum below the 'knee' is found to be

\[
\gamma = 2.63 \pm 0.02(\text{stat.}) \pm 0.05(\text{syst.}) \pm 0.05(\text{model}),
\]

where the last error is an estimation of the dependence on the hadronic interaction generator in the MC.

2.3 The Chemical Composition around the 'Knee'

In order to get a first indication of the behaviour of the chemical composition around the 'knee' and in order to check the MC generators, HEGRA made in one analysis the simple ansatz of using parametrized MC distributions for the
energy determination \([6]\). A more involved unfolding procedure based on the full MC and detector information is used in a second analysis described in detail in \([1]\). In both analyses the composition around the 'knee' is observed to be consistent with an unchanged or slightly heavier composition. For illustrating the results and the observed MC dependence the first approach is discussed in the following.

In the energy range from 300 TeV to 3 PeV the height of the individual shower maxima can be reconstructed with an accuracy comparable to the RMS spread for iron showers (\(\text{rms}(X_{\text{max, iron}}) = 33 \pm 2 \text{ g/cm}^2\)) and thus much better than the RMS spread for proton showers (\(\text{rms}(X_{\text{max, proton}}) = 84 \pm 6 \text{ g/cm}^2\)). Since the mean \(X_{\text{max}}\) values of protons and iron showers differ by about 140 g/cm\(^2\), the fractions of light (hydrogen and helium) and heavy elements (oxygen and iron) contributing to the measured distribution can thus be obtained from fitting model \(X_{\text{max}}\) distributions to the data for different energy bins. The details of this analysis can be found in \([2]\). Under the assumption that the chemical composition is the same for the different energy bins, the mean fraction of light elements is fitted to be 0.52 \(\pm 0.10\) (total error), which within errors, is compatible with direct measurements below 100 TeV.

Besides the shape of the \(X_{\text{max}}\) distribution the mean value may serve to
determine the elemental composition. The measured mean values, however, turn out to be systematically smaller by $45 \pm 24$ g/cm$^2$ than expected from MC for the composition compatible with the fitted fractions which are based on the detailed shape of the $X_{\text{max}}$ distribution. This apparent discrepancy between data and MC can be due to detector, atmospheric, or MC generator effects. After careful investigations HEGRA now suspects the longitudinal shower development in the MC to yield too large $X_{\text{max}}$ values due to a non-perfect simulation of the longitudinal shower development. The investigations, however, are not yet completed. Note that the AIROBICC-type detectors as employed e.g. by HEGRA are the only airshower detectors which are sensitive to the absolute position of the shower maximum due to the translation of the longitudinal development into the radial Cherenkov photon density. This is a consequence of the varying refractive index and height of emission along the shower.

Like HEGRA, the KASCADE collaboration also finds little change in the chemical composition around the 'knee' \[7\]. The absolute determination which relies on the MC is, however, still biased by large discrepancies between some of the hadronic interaction generators. Here still considerable effort is needed in order to achieve reliable results in the future.

3 Gamma-Ray Astronomy

Since the detection of the Crab nebula as a source of gamma-rays ($\gamma$-rays) with energies above 500 GeV in 1989 \[9\], about 10 galactic and extragalactic sources of very high energetic photons ($E > 300$ GeV) have been detected by about as many experiments. The status of the field is indicated in fig. 3 which shows the skymap of the very high energy (VHE), i.e., $E > 300$ GeV, $\gamma$-ray sources as of August 1997. Note that contrary to former beliefs also extragalactic sources of VHE $\gamma$-rays were discovered during the last 5 years. The fast progress of the field will be illustrated by the most recent HEGRA results concerning the brightest source on the $\gamma$-ray sky in 1997, the active galactic nucleus (AGN) Mkn 501 at a distance of $z = 0.034$ ($\approx$ 600 million light years, for $H_0 = 50$ km sec$^{-1}$Mpc$^{-1}$).

3.1 The HEGRA Cherenkov Telescopes

In 1996 the HEGRA experiment completed the installation of six Imaging Air Cherenkov Telescopes (IACTs). Four identical IACTs are operated in coincident mode, i.e. for each airshower four different views are recorded. Hereby
the energy threshold can be lowered and the $\gamma$/hadron separation efficiency can be raised. This is an advantage for the study of weak and especially for extended sources but is less than optimal for strong point-like sources due to the restricted effective collection area. For the current energy range of IACTs, i.e. above 300 GeV, and the current stage of $\gamma$-ray astronomy, i.e. the discovery age in which we learn how to optimize the detectors, this setup, however, has its merits due to the redundancy of the information. For energies below 100 GeV where air showers only produce very little Cherenkov light, however, the redundancy will be lost to a large degree due to the very limited number of particles above the Cherenkov Threshold, i.e., different telescopes will view different tracks in the shower. In this energy regime therefore very sensitive telescopes like the MAGIC Telescope discussed below will be needed and which will not compromise on the effective photo collection area.

### 3.2 The Extragalactic TeV photon source Mkn 501

Mkn 501 belongs to the blazar class of AGN, i.e. it is an AGN with a large plasma jet which is pointing along the line-of-sight, and it has been observed at TeV energies since 1995 when its activity level corresponded to about 8% of the flux of the strongest galactic source, the Crab nebula. Due to its steady emission level the Crab nebula has become the Standard Candle for $\gamma$-ray astronomy. The activity level of Mkn 501 in 1996 rose to about 30% of the
Crab flux \cite{14} and in 1997 HEGRA recorded on average a flux corresponding to about 200\% of the Crab flux, and, in addition to this much higher average activity level, huge flares on time-scales as short as a day or less were recorded. As summarized in \cite{15} a great number of Cherenkov telescopes (Whipple, CAT, TACTIC, Telescope Array, HEGRA) were able to detect this signal and record a light curve. The most complete light curve was obtained by the stand-alone telescopes CT1 and CT2 of the HEGRA collaboration, because CT1 was also operational during moonshine. The light curve extending from March until September 1997 is shown in fig. 4. The short-term flares point towards very compact sources, i.e. regions in the vicinity of the supermassive ($\mathcal{O}(10^8)M_\odot$) black hole thought to be in the centre of the galaxy and powering the very strong non-thermal emission of the AGN. These large fluxes, which for the first time were recorded from an extragalactic source, allowed the determination of the energy spectrum extending beyond 5 TeV. The energy spectrum as measured by the HEGRA IACT system telescopes in 1997 is shown in fig. 5 \cite{13}. As the analysis of systematic effects at higher energies is not yet completed, the spectrum is only shown up to 10 TeV.

But already the unabsorbed spectrum extending up to 10 TeV allows to extract a fundamentally important upper limit on the density of infrared (IR)
Figure 5: The energy spectrum of the blazar Mkn 501 as measured by HEGRA system telescopes during the 1997 observation campaign. Measured points beyond 10 TeV are not shown.

Figure 6: Energy density of the extragalactic diffuse background radiation. For detailed references see [14]. Solid line: average model from MacMinn & Primack including the CMBR [15]; dashed line: average model from Fall, Charlot & Pei added to the CMBR [16]; dotted line: upper limit derived in [14].
relic photons in intergalactic space. This density is dependent on the era of galaxy formation and thus on the nature of the Dark Matter.

One extraction of an upper limit on the infrared photon density was performed in [14] where it is assumed that the IR background is uniformly distributed in the Universe. The result, together with existing upper limits, lower limits, and an average model for galaxy evolution based on a mixed Dark matter ansatz is shown in fig. 6. The resulting low density of infrared photons limits the parameter space for Dark Matter models and at the same time opens up the deeper regions of the universe (i.e. $z = \mathcal{O}(0.1)$) for TeV astronomy.

3.3 The Future of Gamma-Ray Astronomy

Currently space-borne $\gamma$-astronomy is limited to energies below 10 GeV and ground-based $\gamma$-astronomy to energies above 300 GeV. In both cases the reasons are limitations of sensitivity and/or effective collection areas. The result is an observation gap between 10 GeV and 300 GeV where the Universe has not been observed in and where we expect to find hints or answers to important physics questions in astrophysics, cosmology, and particle physics.

In order to bridge this gap the ground-based 17 m diameter MAGIC Telescope (see fig. 7) has been designed during the last 2 years [17]. Using innovative elements it will be possible to close the last observation gap for about 1% (!) of the cost of a satellite experiment, which until now was believed to be necessary in order to do measurements in this energy domain. At the same
time the sensitivity in the energy region of current Cherenkov telescopes will be improved by up to an order of magnitude.

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