The Cosmic-Ray Proton Spectrum as measured with the HEGRA System of Imaging Atmospheric Čerenkov Telescopes

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Abstract

The HEGRA collaboration operates a *stereoscopic* system of 5 imaging atmospheric Čerenkov telescopes (IACT) at La Palma (Canary Islands). This instrument has been used to measure the spectrum of the Cosmic Ray (CR) protons in the energy range of 1-10 TeV. The high detection rate of about 12 Hz for the CRs, the effective suppression of air showers induced by heavy nuclei on the trigger level as well as by the software analysis, and the 50% energy resolution for proton-induced air showers, allow us to determine the spectrum of the CR protons. The data are well reproduced by a power-law over the entire energy range. The best fit to the data at ~3 TeV gives a differential spectral index of $2.72 \pm 0.02(stat) \pm 0.15(syst)$ and an integral proton flux $\mathrm{J}(> 1.5\,\mathrm{TeV}) = (3.1 \pm 0.6 \pm 1.2) \cdot 10^2$ particles $\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{m}^{-2}$, consistent, within the statistical and systematic errors, with recent satellite and balloon-borne measurements.

1 Introduction:

The HEGRA experiment is a multicomponent detector consisting of a number of different instruments (see Lindner, et al., 1997). The *stereoscopic* system of Imaging Atmospheric Čerenkov telescopes of the HEGRA collaboration is a powerful tool for detecting TeV γ-ray sources and for performing detailed spectroscopic studies in the energy range from 500 GeV to $\sim$ 50 TeV, where the latter limit is determined by event statistics alone. With the nearly background-free detection of γ-rays from the Crab Nebula, an energy flux sensitivity $(\nu\, F_\nu) \simeq 10^{-11}\,\mathrm{ergs\,cm^{-2}\,s^{-1}}$ at 1 TeV for one hour of observational time has been estimated. The high signal to noise ratio together with the energy resolution of better than 20% for primary photons makes it possible to study the spectra of strong sources on time scales of one hour, as demonstrated by the observation of the BL Lac object Mkn 501 during its 1997 state of high and variable emission (see Aharonian et al., 1999a). The IACT system can not only be used for γ-ray astronomy. It can also contribute to the study of charged cosmic rays (CR) for energies between a few TeV and possibly $\sim$ 100 TeV, a key energy region for the understanding of the sources of CRs and their propagation through our galaxy.

The measurement of the spectrum of cosmic ray protons with the IACT array described here has systematic uncertainties comparable to recent measurements of satellite and balloon borne experiments (e.g. see Wiebel-Sooth et al., 1998). A clear advantage of the IACT technique is the large effective area of $\simeq 3{\cdot}10^3$ m^2 sr for TeV cosmic rays combined with a field of view of $\simeq$ 3 msr, corresponding to a detection rate of around 12 Hz for $>$ 1 TeV cosmic rays. The *stereoscopic observation* of air showers with at least two IACTs suppresses the rate of heavier primaries already on the trigger level. This is because the energy threshold $\mathrm{E_{thr}}$, defined as the energy where the differential detection rate peaks, increases substantially with the nucleon number A, approximately as $\mathrm{E_{thr}} \propto A^{0.5}$. The stereoscopic detection of the air shower under different viewing angles with high resolution imaging cameras permits us to unambiguously reconstruct the air shower axis in three dimensions. Knowing the location of the shower core with a precision of 30 m, the energy of a primary proton can be determined with an accuracy $\Delta E/E$ of 50% and the different projections of the longitudinal and lateral shower development can be used to obtain an event sample enriched with particles of a certain primary species (see Aharonian et al., 1999b). We have applied this method to data from the HEGRA experiment, that accumulates CR air shower data in the form of background events during γ-ray observations. The results of the analysis are presented here.

2 The HEGRA array of IACTs

The HEGRA collaborations operates the *stereoscopic* system of 5 imaging atmospheric Čerenkov telescopes. The experiment is located on the Canary Island La Palma at the Observatorio del Roque de los Muchachos (2200 m a.s.l., 28.75° N, 17.89° W). Each telescope is equipped with a 271 pixel camera, covering a field of view of 4.3°. The pixel size is 0.25°. The cameras are readout by an 8 bit 120 MHz Flash-ADC system. The telescope system uses a multi level trigger scheme. A coincidence of two neighboring pixels from 271 above a given threshold (8 ph.e.) triggers an individual telescope. A coincidence of at least two telescopes triggers the telescope system and results in the readout of the buffered FADC information of all telescopes. An absolute calibration of the system has been performed with a laser measurement and a calibrated low-power photon detector. This measurement has determined the conversion factor from photons to FADC counts with an accuracy of 12%. The error on the energy scale is estimated to be 15% which derives from the uncertainty in the conversion factor from Čerenkov photon counts to FADC counts, and from the uncertainty in the atmospheric absorption. To obtain the data used in the present analysis, the photomultipliers were operated in a regime where saturation effects are smaller than 10%, for less than 400 photoelectrons per pixel. A total amplitude of the image, the *Size*, of 400 photoelectrons represents an energy of protons of around 15 TeV.

3 Simulations

The cosmic ray air showers have been simulated with the ALTAI code (see Konopelko et al., 1999). In order to study the model dependence of the observable parameters, a second air shower library was generated, using the CORSIKA code (Capdevielle et al., 1992) to simulate the hadronic interactions of the air shower cascade. High energy interactions ($E_{\rm CM} > 80$ GeV) were simulated with the HDPM model. Low energy interactions ($E_{\rm CM} < 80$ GeV) were modeled with the GHEISHA model. Instead of EGS our version of CORSIKA uses the ALTAI code to model the electromagnetic shower development.

A comparison of the essential characteristics was performed using $5 \cdot 10^5$ proton- and Helium-induced air showers of vertical incidence, simulated both with the ALTAI and the CORSIKA hadronic interaction models in an energy range of 0.3 to 50 TeV and a distance scale of 250 m to the central telescope of the system. The difference between the two models is smaller than 10% over the entire energy range. Although completely different interaction models have been used, the agreement is excellent. The predictions of both models for the HEGRA cosmic ray detection rates are in very good agreement.

After the air shower generator, the showers were processed with a new detector simulation routine for the HEGRA array of IACTs. This routine includes a full detector simulation procedure, taking into account atmospheric absorption and scattering of Čerenkov photons in atmosphere, reflecting by the telescope mirror, the arrival times of the Čerenkov photons, the photomultiplier (PM) response and the characteristics of the electronic chain to derive the trigger decision and the digitized signal. The new simulations permit an identical treatment of Monte Carlo simulated showers and real data (see Hemberger, 1998).

4 Analysis

The proton component can effectively be separated from heavier cosmic rays over the energy range from 1 to more than 10 TeV (see Plyasheshnikov et al., 1998). Note that apparently the suppression of heavier nuclei is best after the system triggering. A further important suppression of heavier particles was achieved by an analysis of the stereoscopic IACT images which shape is affected by the longitudinal and lateral shower development. We analyzed the data using the parameter *mean scaled Width*. For each telescope i the *Width*-value is normalized to the value expected for a proton shower $\langle\, W(\mathit{Size}_i, r_i)\,\rangle_{\rm MC,p}$ given the sum of photoelectrons of the image, Size_i, and the distance r_i of the shower core from the telescope. The values obtained from the $n_{\rm tel}$ triggered telescopes were combined to the quantity (see Konopelko et al., 1999)

$$W_{\rm scal} = 1/n_{\rm tel} \sum_i^{n_{\rm tel}} W_i(\mathit{Size}_i, r_i)/\langle\, W(\mathit{Size}_i, r_i)\,\rangle^p_{\rm MC}. \qquad (1)$$

The $W_{\rm scal}$-parameter, taking into account the distance and amplitude dependence of the image width, allows to enhance proton induced showers among showers induced by all particles. A cut at *Width*$_{\rm scal} < 0.85$, for example, accepts $\sim 48\%$ of the primary protons, but only 20% of the primary helium, and $\simeq 10\%$ of the heavier nuclei. The main advantage of scaling the *Width*-parameter consists in energy independent cut efficiencies for proton-induced air showers and almost energy independent cut efficiencies for the heavier primaries. Finally, at energies between 1 and 10 TeV the combined effect of suppression of heavier nuclei by the detection principle and by the image analysis enriches the data sample with proton-induced showers by a factor of 10.

For each triggered telescope, an *energy estimate* E_i of the primary particle was computed under the hypothesis of the primary particle being a proton, from the image size, *Size*$_i$, measured in the ith telescope at the distance r_i of the telescope from the shower core. Averaging over all triggered telescopes gives a common energy estimate. The energy estimate E_i was determined by inversion of the relation *Size*$_i = \langle$ *Size*$(E, r) \rangle_{\rm MC,p}$ between primary energy E, impact distance r_i and expected image size *Size*$_i$, as computed from the Monte Carlo simulations for proton induced showers. This method leads to an energy resolution $\Delta E/E$ of $\approx 50\%$ for primary protons.

The proton spectrum was determined using the standard method of *forward folding*. The Monte Carlo events of the particle group i were weighted to correspond to a power law for the flux dF/dE $= \alpha \cdot n_i$ E$^{-\gamma_i}$ where the n_i and the γ_i (except the γ_i of the proton component) reflect the assumed chemical composition. The fitted parameters are the common scaling parameter α and the spectral index of the proton component γ_p. These two parameters were varied until the χ^2-difference of the observed histogram of reconstructed energies and the corresponding histogram predicted with the weighted Monte Carlo events is minimized. The fit was performed in the range from 1.5 to 3 TeV of the reconstructed energy. The contamination of the data sample with heavier particles is small, especially in the energy range from 1 to 3 TeV, and therefore the result depends only slightly on their assumed abundances and spectral index, even though this dependence has been studied in detail.

5 Data sample

We used the data primarily taken for the observation of Mkn 501 during 1997. Only runs taken under excellent weather and hardware conditions were accepted (53.2 hrs in total).

The Mkn 501 data set was used because of its large fraction of small zenith angle data (up to 20°). The solid angle region around Mkn 501 does not contain very bright stars which cause excessive additional noise. As a matter of fact, the strong γ-ray beam from Mkn 501 in 1997 did not only supply informations of astrophysical interest, but made it in addition possible to test the simulation of electromagnetic showers and the simulation of the detector response to these showers with unprecedented statistics (38,000 photons were recorded). The γ-rays could easily be excluded from the analysis by rejecting all showers reconstructed within 0.3° from the source direction.

Identical cuts were applied to the measured data and the Monte Carlo data. In addition to the cuts already mentioned above, a cut on the distance r of the shower axis from the central telescope of $r < 175$ m was applied. Only telescopes with a distance r_i smaller than 200 m from the shower axis entered the analysis, suppressing by these means images close to the edge of the camera.

6 Results

The forward folding method gives a best power law fit to the data in the energy range from 1.5 to 3 TeV for:

$$\frac{{\rm d}F}{{\rm d}E} = (0.11 \pm 0.02_{\rm stat} \pm 0.05_{\rm sys}) \cdot E^{-(2.72 \pm 0.02_{\rm stat} \pm 0.15_{\rm sys})} \, {\rm particles\, s^{-1}\, sr^{-1}\, m^{-2}\, TeV^{-1}}. \qquad (2)$$

A power law fits the data very well (see Figure 1). The systematic error on the spectral index is dominated by the Monte Carlo dependence of the results and by the contamination of the data sample by heavier particles. The systematic error of the absolute flux is affected in addition by an uncertainty in the energy scale of 15%. We obtain an integral flux above 1.5 TeV of $F(> 1.5\,{\rm TeV}) = 3.1 \pm 0.6_{\rm stat} \pm 1.2_{\rm syst} \cdot 10^{-2}\, particles\; s^{-1}\; sr^{-1}\; m^{-2}$.

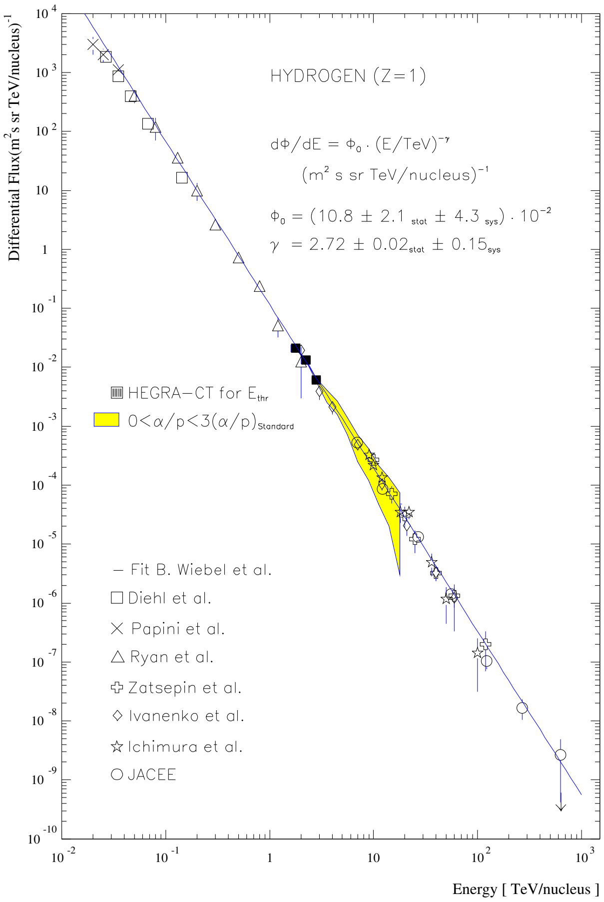

Figure 1: The energy spectrum of cosmic ray protons as measurement with the HEGRA array of IACTs. The results of previous satellite and balloon-borne instruments are also indicated. The shaded area represents the systematic error of our measurement caused by a variation of the assumed α/p-ratio over the range $0 < \alpha/\mathrm{p} < 3(\alpha/\mathrm{p})_{\mathrm{Standard}}$ relative to $(\alpha/\mathrm{p})_{\mathrm{Standard}} = 0.61$.

Our results are in very good agreement with recent results of satellite and balloon-borne experiments (see Figure 1).

In future work we shall attempt to extend the measurement of the proton spectrum to higher energies. This might be possible by increasing the software threshold despite decreasing statistics. Improved cuts should also yield information about the spectrum of heavier nuclei.

7 References

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