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Measurement of the energy spectrum of light cosmic rays with the HEGRA air shower arrays

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Abstract. Data of the HEGRA scintillator and AIROBICC arrays have been used to determine the energy spectrum of the light component (p+α) of charged cosmic rays in the energy range between $3{\cdot}10^{14}$ eV and 10^{16} eV. The air showers initiated by light nuclei are separated from those of heavier nuclei by applying an energy dependent cut on the reconstructed depth of the air shower maximum. The energy spectrum of the light component can be described by two power laws with a smooth transition at an energy around $3 \cdot 10^{15}$ eV.

1 Introduction

The energy spectrum of cosmic ray particles shows a slight change in slope at energies of roughly 3-6 PeV (1 PeV= 10^{15} eV) traditionally referred to as 'the knee'. Neither the origin of cosmic rays in general nor the cause of the knee are known. The often cited paradigm of shock acceleration of charged particles in the expanding shell of supernova remnants is considered to be a likely explanation of Galactic cosmic rays. However, an experimental confirmation is still not available. An indirect approach to identify the accelerators of cosmic rays is to determine the energy spectrum and chemical composition over a broad range in energy, preferably covering the knee region. In this paper we determine the energy spectrum of light particles. In the framework of shock acceleration, particles are expected to show a rigidity dependent cut-off. Therefore, the light component (making up a fraction of 40-50 % of the all-particle flux) in the cosmic ray spectrum should show a steepening as well.

The HEGRA air shower arrays are measuring simultaneously Cherenkov light in a non-imaging setup and charged particles from extended air showers have been used to determine the energy spectrum of the light component of charged cosmic rays (essentially p and α particles). In section 2 the experimental setup will be described, section 3 gives details to the analysis technique and section 4 contains the results of the analysis that are compared with recently published models of cosmic ray acceleration.

2 Experimental setup and data sample

The HEGRA air shower arrays have been operating in changing setups in the years 1989-2000. An outstanding feature of the detector complex is the AIROBICC array (Karle et al., 1995). Up to 97 open large diameter (20 cm) Photomultiplier tubes are used to detect Cherenkov light from extended air showers. The AIROBICC array is complemented by an array of scintillation counters (up to 243 individual stations) recording charged particles. The detectors were installed on an area of $200{\times}200$ m^2 on the Canary island La Palma at an altitude of 2 200 m above sea level (790 g/cm^2 atmospheric overburden). The arrays sample the shower front and the Cherenkov light of extended air showers and allow to reconstruct the direction of the shower axis by relative timing. The energy is determined by measuring the light intensity and the particle density respectively.

The data analyzed were collected in the years 1995 through 1997 with a setup of 49 AIROBICC detectors and 243 Scintillation counters. The data cleaning procedure to ensure a homogenous data sample is tuned to reject nights with unfavorable atmospheric conditions and failures in the detector performance. The data sample comprises a total of 380 hours of data taking. The statistics of 36 million collected air showers is sufficient to measure the energy spectrum up to energies of approximately 10 PeV. At energies beyond 10 PeV the detectors show symptoms of saturations that can not be recovered without introducing considerable systematic errors. The systematic error at energies at and above 10 PeV start to dominate over the statistical error of the analyzed data sample. The zenith angle of reconstructed air shower direction has been constrained to be less than 15° and the reconstructed position of the core is required to be within the bounds of the experiment. Further details of the data selection procedure are given in Röhring (2000)

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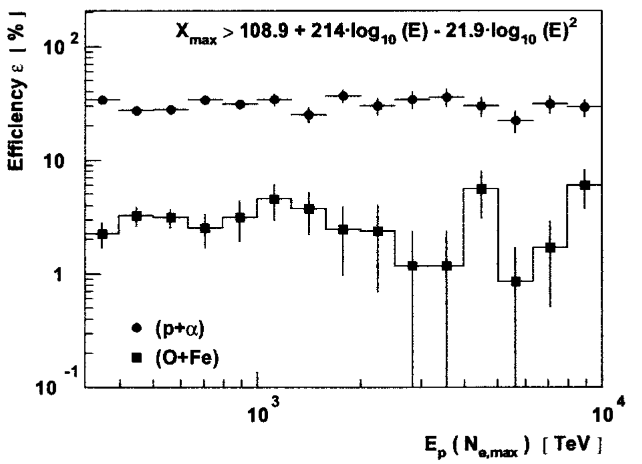

Fig. 1. The efficiency for light (p+α) and heavy elements after applying the cut given in Eq. (2) on the X_{max}-distribution. The lines indicate the efficiency that is used to correct the data. The result is based upon Monte Carlo simulated air shower data taking the experimental resolution into account.

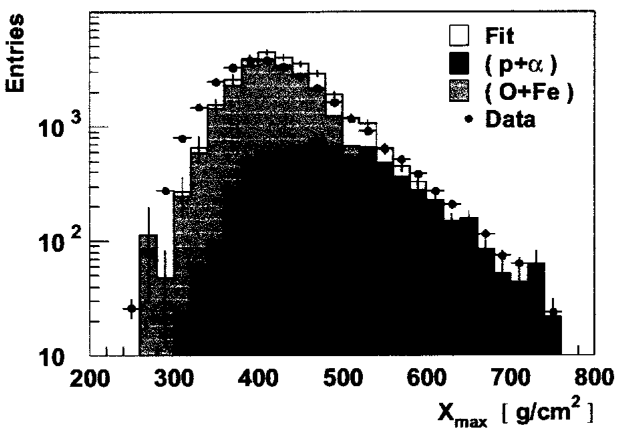

Fig. 2. As an example of the reconstructed distribution of X_{max} the data together with the results of Monte-Carlo simulations are shown for air showers with $\langle E \rangle = 708$ TeV from the energy interval 582 TeV $< E(N_{e,max}) <$ 1 PeV The distribution of X_{max} of the simulation has been fit to the data. Details of the fitting procedure are described in Arqueros et al. (2000).

3 Analysis methods

3.1 Energy reconstruction

The analysis is based upon energy reconstruction methods developed specifically for a setup consisting of Cherenkov light and particle detectors. The general method described in Lindner (1998) uses the position of the shower maximum to infer the energy per nucleon. Using the energy per nucleon as input the energy of the primary particle can be reconstructed from the intensity of Cherenkov light (L_{90}, see text below for details on this quantity) or from the number of particles at the position of the shower maximum ($N_{e,max}$) independently from the particle species.

The most important observable of this method is the position of the shower maximum X_{max} that is reconstructed from the shape of the lateral distribution of Cherenkov light detected at the observation level. The absolute accuracy for the reconstruction of the position of the shower maximum X_{max} is smaller than 40 g/cm^2. The relative energy resolution $\Delta E/E$ achieved with the particle independent method is 30 % for energies larger than 300 TeV improving with increasing energy.

However, for a known particle species it is straightforward to reconstruct the energy from the amount of Cherenkov light (L_{90}) or the number of particles in the shower maximum. The number of particles in the shower maximum ($N_{e,max}$) is reconstructed by combining the information from the lateral shape of the Cherenkov light distribution and the number of particles measured by the scintillator detectors. In contrast to the number of particles impinging on the observation level, the number of particles in the shower maximum shows only marginal fluctuation, thus it is possible to achieve a good relative energy resolution of $\Delta E/E \approx 15\,\%$ improving with increasing energy. The energy $E_p(N_{e,max})$ for example, is the energy reconstructed for an assumed proton as primary particle using the number of particles at the position of the shower maximum:

$$E_p(N_{e,max}) \quad = \quad (N_{e,max}/508.16)^{0.993}\,\text{TeV} \qquad (1)$$

A convenient and robust parameter for the Cherenkov light intensity is the amount of light measured at a distance close to the hump in the lateral distribution of the Cherenkov light. In this case the light intensity at 90 m distance has been chosen: L_{90} The relative energy resolution obtained with the energy reconstruction method using the Cherenkov light alone ($E_p(L_{90})$) is comparable with the reconstruction accuracy of $E_p(N_{e,max})$.

3.2 Extracting light particle energy spectra

The position of the shower maximum varies with the energy per nucleon: $X_{max} = a \cdot \log_{10}(E/A) + b$. For a given primary energy E, the mean penetration depth for a nucleon with mass A is shifted by $-a \cdot \log_{10}(A)$ with respect to a proton initiated air shower of the same energy. Since the position of the maximum number of particles fluctuates with the position of the first interaction and intrinsic fluctuations of the shower development, the distributions of X_{max} show a width of $\approx$ 90 g/cm^2 for proton initiated showers and respectively $\approx$ 40 g/cm^2 for iron induced showers as the opposing extreme. The constants a and b are independent of the particle species. In Monte Carlo air shower simulations we have determined the values for a = 74.5 g/cm^2 and b = 329.4 g/cm^2 using CORSIKA version 5.2 (Knapp & Heck, 1993) with the interaction model QGSJET (Kalmykov et al., 1997). The analysis of the light component in the cosmic ray energy spectrum is based upon rejecting a large fraction of the air showers initiated by heavy primaries ($A > 4$) by applying

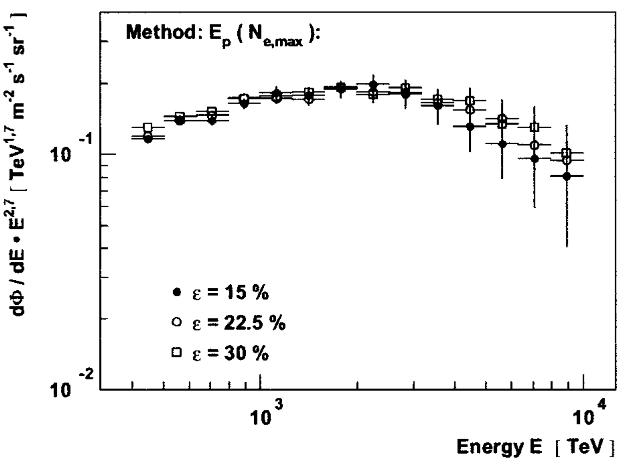

Fig. 3. Comparison of three energy spectra of the light component reconstructed with different cuts on the X_{max}-parameter (efficiencies of 15 %, 22.5 % and 30 % have been used). The agreement of the corrected energy spectra prove consistency between data and Monte-Carlo simulations.

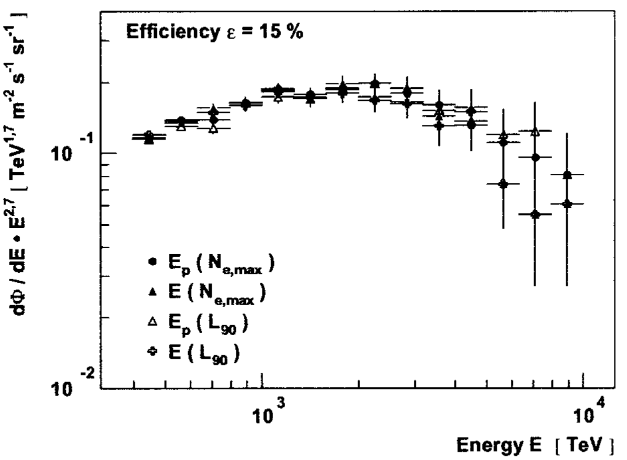

Fig. 4. Comparison of different energy spectra, derived from the number of particles at the position of the maximum of particles in the shower development ($N_{e,max}$) and from the Cherenkov light intensity L_{90} with and without assuming a certain particle species. The good agreement indicates that the energy reconstruction method is not causing systematic effects.

a cut on the reconstructed distribution of X_{max} for a given energy interval. The cut is chosen to keep the efficiency for accepting air showers with $A \leq 4$ constant at 30 % for the whole energy range. At the same time heavy particles are rejected at the level of 97 %.

The cut on X_{max} is chosen to be:

$$X_{max}^{30\,\%} \quad > \quad 108.9 + 214 \cdot E_{lg} - 21.9 \cdot E_{lg}^2 \qquad (2)$$

with $E_{lg} = \log_{10}(E_p(N_{e,max}))$. Note that a quadratic term is implemented to account for the shift of the $\langle X_{max}(E) \rangle$ in the reconstructed energy interval because of the correlation between X_{max} and the energy (Arqueros et al., 2000). In Fig. 1 the efficiency for light and heavy particles is plotted as a function of energy. This result is obtained from Monte-Carlo simulations taking the experimental resolution into account. The distribution of X_{max} from Monte-Carlo simulations shows good agreement with the respective distribution from data (see Fig. 2). The only significant deviations are seen for small values of X_{max}. Since the efficiency for light particles is not dependent upon the exact shape of the distribution for small values of X_{max} we assume that the calculated efficiency from Monte-Carlo is correct. After applying the cut on the events within a given energy interval, the number of remaining air showers is divided by the width of the energy interval, the dead time corrected observation time, the collection area of the experiment and the solid angle covered. The flux is then divided by the efficiency for acceptance of air showers with $A \leq 4$ after applying a cut on $X_{max}(E)$.

The cut on $X_{max}(E)$ is chosen such that this efficiency remains constant for all particle species within the whole energy range. The result is the differential flux of primary particles with $A \leq 4$ in the energy range from 300 TeV to 10 PeV. The differential flux multiplied by $E^{2.7}$ is displayed in Fig. 3. To check for systematic uncertainties, different cuts with varying efficiencies have been applied. The corrected flux values are in excellent agreement for the different cut efficiencies which proves that data and Monte-Carlo simulations are consistent.

To check the influence of the energy reconstruction on the reconstructed light particle spectrum, in Fig. 4 the energy spectra obtained with different methods of energy reconstruction are compared with each other. It is evident, that the energy reconstruction method is not causing any systematic effect, which is comforting in a sense that the particle dependent and independent method give the same result.

4 Discussion

The general shape of the energy spectrum of light elements shows a smooth transition between two power laws. The energy region of transition stretches from 2 to 4 PeV. There is no indication for a cut off at lower energies as observed by the CASA-MIA experiment (Glasmacher et al., 1999). The results presented here indicate that the accelerators of Galactic cosmic rays efficiently reach energies of a few PeV for proton and α particles. In Fig. 5 the energy spectrum using $E_p(N_{e,max})$ and a cut efficiency of 30 % is compared with the predictions of recent model calculations for the energy spectrum of the light component under different assumptions. The HEGRA energy spectrum is in agreement with the model calculations of Kalmykov and Pavlov (1999). The model of Berezhko and Ksenovontov (1999) predicts also a flat energy spectrum with a smooth transition to a steeper spectrum at a few PeV. The models labeled TIBET in Fig. 5 are taken from Amenomori et al. (2000), showing two extreme cases of energy spectra with proton dominated (PD) and heavy dominated (HD) chemical compositions. The PD model is favored

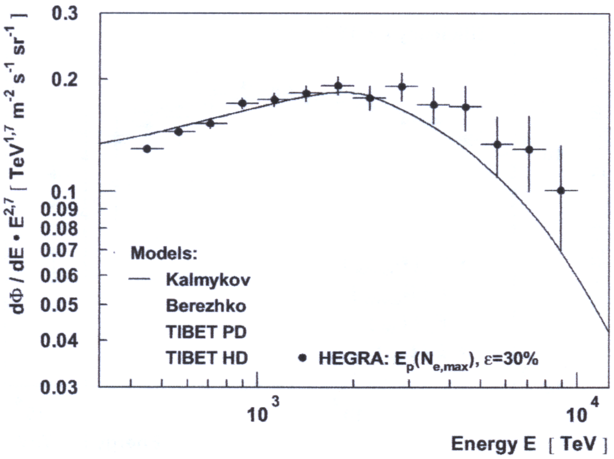

Fig. 5. The energy spectrum of light charged cosmic rays in comparison with predictions of recent models of transport and origin of Galactic charged cosmic rays. See the text for details and references to the different models.

by the Tibet air shower array data showing a cut off of the proton energy spectrum at 100 TeV, which is not consistent with the result presented here.

The results of direct and indirect measurements of the energy spectra of proton and α particles are compiled in Fig. 6. The absolute flux determined by direct experiments (Apanasenko et al., 1999; Asakimori et al., 1998) connects smoothly with the results of this work. However, there is substantial disagreement on the shape of the energy spectra as observed by CASA-MIA (Glasmacher et al., 1999) and the Tibet air shower array (Amenomori et al., 2000) on the one hand and KASCADE (Hörandel, et al., 2001) and HEGRA (this work) on the other hand.

The energy spectrum of light particles as determined by KASCADE shows over-all a similar shape whereas the absolute flux calibration is not completely consistent. The differences are well within the systematic error of the absolute energy calibration which relies solely on Monte-Carlo methods and is obviously the major contribution to uncertainties.

5 Summary

The HEGRA air shower arrays have been used to determine the energy spectrum of the light component of the charged cosmic rays (mostly proton and α particles). Different methods of energy reconstruction have been applied to the data. As a systematic check, a primary particle independent method to reconstruct the energy has been compared with primary particle dependent methods.

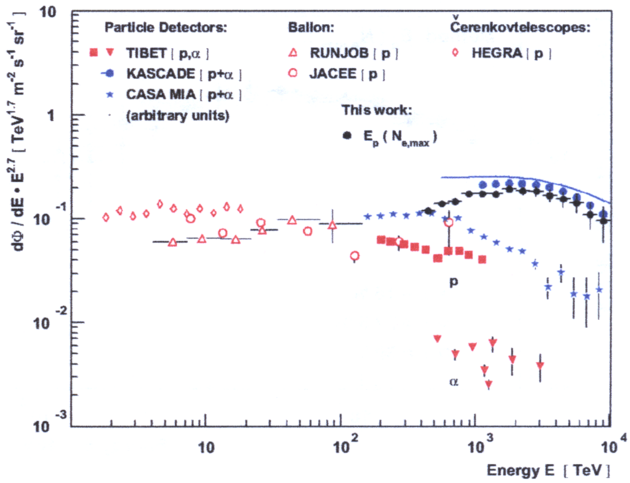

Fig. 6. Results of this work are compared with a compilation of recent data available from direct experiments:JACEE (Asakimori et al., 1998), RunJob (Apanasenko et al., 1999); Cherenkovtelescopes: HEGRA (Aharonian et al., 1999), air shower detectors: Tibet (Amenomori et al., 2000), KASCADE (Hörandel, et al., 2001), CASA-MIA (Glasmacher et al., 1999).

Light particles are separated efficiently from heavier nuclei by cutting on the position of the maximum number of particles in the shower development (X_{max}) reconstructed from the lateral shape of Cherenkov light intensity distribution. The resulting energy spectrum shows a flat behaviour with a gradual steepening of the spectral index between 2 and 4 PeV. This spectral shape is suggested in the framework of recent theoretical predictions.

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