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The energy spectrum of the H+He mass group of cosmic rays in the TeV region measured with HAWC

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The investigation of the energy spectrum and the mass composition of cosmic rays in the 1 TeV - 1 PeV energy range is an important topic in astroparticle physics, as it can provide clues to understand the origin, acceleration mechanism and propagation of high-energy cosmic rays in our galaxy, as well as to find out the link between the TeV and the PeV cosmic-ray radiation. At HAWC, extensive air showers (EAS) from TeV cosmic rays are recorded at a rate of 25 kHz using a 22000 m^2 array of 300 water Cherenkov detectors, each of them instrumented with 4 photomultipliers. The instrument measures different shower observables such as the arrival direction, the core position at ground, the lateral age and distribution and the primary energy, which allow to perform a variety of studies on the energy spectrum, composition and arrival direction of TeV cosmic rays. In this work, we have estimated the energy spectrum of H+He nuclei of cosmic rays between 6 TeV and 158 TeV. The spectrum was obtained by applying a Bayesian unfolding method on a subsample of air-shower data, which has a purity of 82% of H+He induced events. The spectrum was corrected for the contamination of heavy cosmic-ray nuclei. The subsample was extracted from the measured data by applying an energy dependent cut on the shower age of the events that was derived from Monte Carlo simulations with QGSJET-II-04. We found the existence of a cut in the spectrum of H+He cosmic ray nuclei close to 24 TeV with a statistical significance of 4.1 σ.

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1. Introduction

One of the science objectives behind the construction and operation of the HAWC observatory is the physics of cosmic rays at TeV energies. HAWC was originally designed to look for the sources of galactic cosmic rays, to study the physical conditions of astrophysical environments involving particle acceleration and to search for transient events with high-energy emission by means of observations of the universe in TeV gamma rays [1]. For this aim, the observatory exploits the air-shower detection technique at high altitudes [2], which also permits the study of the TeV cosmic-ray flux [3]. HAWC investigations on TeV cosmic rays have allowed the measurement of the total energy spectrum and the large- and small-scale anisotropies in the sky map of these particles. The data used in the analysis of the all-particle spectrum of cosmic rays have led to the observation of a softening in the spectrum at ~ 46 TeV [3], while the measurements on the arrival directions of cosmic rays, in combination with observations from ICECUBE, have allowed to get the first anisotropy map of cosmic rays of almost all the sky at a median energy of 10 TeV [4]. HAWC studies have also been extended to cover analyses of the composition of cosmic rays. A precise measurement of the energy spectrum of H+He between 6 TeV and 158 TeV with HAWC has confirmed the existence of a cut at tens of TeV in this spectrum [5], while a preliminary analysis carried out in [6] with data from the observatory has pointed out that the softening in the spectra of H plus He cosmic-ray nuclei is the result of the superposition of individual cuts in the intensities of these primaries. The presence of such features in the elemental spectra of protons and helium nuclei was first suggested by CREAM I-III [7] and NUCLEON [8], and later confirmed by DAMPE [9, 10]. Now HAWC also supports the existence of those structures. In addition, HAWC data also seem to reveal individual hardenings in the cosmic-ray spectra of H and He nuclei at approximately 100 TeV [6]. Further cosmic-ray analyses are in progress, but with these examples, we demonstrate the capabilities of the HAWC observatory as a cosmic-ray detector at TeV energies. In this work, we will focus on one of the first analysis of HAWC on the composition of cosmic rays, which is related with the measurement of the spectrum of the H+He mass group from 6 TeV to 158 TeV [5]. In the next sections, we present a brief description of the HAWC experiment, the data and the reconstruction method of the spectrum, then we describe the main sources of statistical and systematic uncertainties and their contributions to the result, next we compare our spectrum with other experimental measurements on the intensity of H+He primaries. Finally, we end with a quick discussion about our findings and with our conclusions. More details about the analysis can be found in [5].

2. The HAWC detector and the data

HAWC is deployed on a plateau at 4100 m a.s.l. at the Sierra Negra volcano in the east part of Puebla, Mexico [2, 11]. The instrument is composed of two arrays of water Cherenkov detectors: a central and compact one with an area of 22000 m^2 that includes 300 detector units with dimensions 7.3 m diameter $\times$ 4.5 m deep with 4 photomultipliers (PMTs) each, and a sparse outrigger array that covers 4 times the area of the central detector and contains 345 detectors of smaller dimensions (1.55 m diameter $\times$ 1.65 m height), each of them instrumented with one PMT [12]. For the present analysis, we used data from the central detector collected during the observation period from June 2015 to June 2019. The data are reconstructed with the HAWC offline software [2, 3, 11], which provides estimations about the impact point of the shower core, the arrival direction of the primary particle, the lateral distribution of the deposited charge (LDF), the lateral shower age and the primary energy of the EAS among other observables. In HAWC, the primary energy $E_{\rm rec}$ of the hadronic showers is calibrated event-by-event with Monte Carlo simulations using predictions of CORSIKA[13] and QGSJET-II-04 [14] for proton primaries and a maximum likelihood fit to the deposited charged at the PMTs [3]. Meanwhile, the shower age is obtained from a fit with a Nishimura-Kamata-Greisen type function to the LDF of the event using a chi-squared technique [11]. We refer the reader to [2, 3, 11] for more details about the reconstruction procedures of air-showers in HAWC. With the purpose of reducing the impact of systematic effects in the present analysis, we have applied several selection criteria to the data. In particular, only shower events that were successfully reconstructed and that have shower axis with zenith angles between $\theta_{\rm min} = 0°$ and $\theta_{\rm max} \sim 17°$ were considered. We also required that the events had a fraction of activated PMTs ≥ 0.2, more than 39 PMTs with signals within a circular area of 40 m radius from the shower core and estimated shower energies in the range $\log_{10}(E_{\rm rec}/{\rm GeV}) = [3.5, 5.5]$. After applying our selection cuts, we kept 1.6×10^{10} EAS events.

3. The analysis method

As a first step to estimate the energy spectrum of H+He cosmic-ray nuclei, we applied an energy dependent cut on the lateral shower age of the measured data in order to extract a sample of young shower events, which are dominated by EAS induced by H and He primaries. The reasons are that these species tend to produce air showers with relative small values for the lateral age [15] and that H and He primaries are the most abundant nuclei in the energy spectrum of cosmic rays at tens of TeV [16]. To derive the shower-age cut, we employed MC simulations, which were produced using the CORSIKA software [13] with the FLUKA [17] and QGSJET-II-04 [14] hadronic interaction models. We simulated EAS for H, He, C, O, Ne, Mg, Si, and Fe primaries with energies from 5 GeV to 2 PeV following a power-law spectrum E^{-2}. We weighted the elemental spectra according to the nominal cosmic-ray composition model described in [3]. To simulate the interactions of the shower particles with the detector, we used GEANT4 [18]. while for the reconstruction of the EAS events, we employed the HAWC offline software. Using these MC data sets, we estimated the mean values of the lateral shower age as a function of the primary energy for each primary mass (see left plot of Fig. 1). We put the shower age cut at the middle between the predictions for the mean shower age of He and C primaries to keep a substantial number of events in the selected data sample (62% of the initial events and 64% of the original H and He nuclei) and to have a large percentage of H and He nuclei in this data set (above 82%). After applying the shower-age cut, we got a data subset of 9.9×10^9 events. Its raw energy histogram is plotted on the right panel of Fig. 1.

Next, we corrected the selected subsample of young EAS for migration effects in neighbor bins of $E_{\rm rec}$, which are associated with the experimental resolution of the instrument. This was done using the Bayes' unfolding method [19] and employing the minimum of the Weighted Mean Squared Error [20] as a stopping criterion. For the unfolding procedure, we employed a response matrix, which was estimated from our MC simulations with the nominal composition model of cosmic rays (c.f. Fig. 2, left panel).

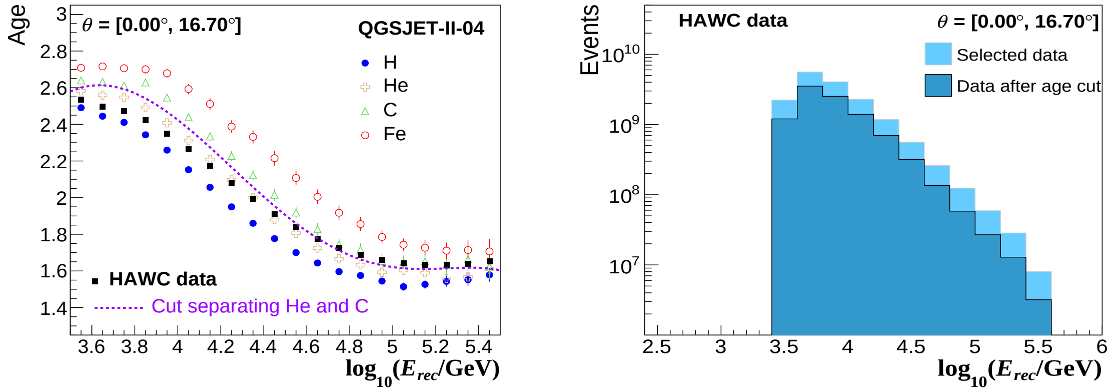

Figure 1: *Left: The expected lateral shower age for H (filled circles), He (crosses), C (triangles) and Fe (open circles) nuclei according to CORSIKA/QGSJET-II-04. The mean values are plotted as a function of the reconstructed energy. The shower-age cut is also shown with a dashed line. For comparisons, the mean of the shower age for the selected HAWC data is also presented (black squares) [5]. Right: Raw energy distributions for the experimental data sample selected with our quality cuts (light blue) and for the subset of young EAS events, which is obtained after applying our shower-age cut (dark blue) [5].*

Finally, we estimated the energy spectrum using the formula

$$\Phi(E) = \frac{N(E)}{\Delta E \, \Delta\Omega \, T_{\text{eff}} \, f_{\text{corr}}(E) \, A_{\text{eff}}^{\text{H+He}}(E)}, \tag{1}$$

where $N(E)$ is the unfolded energy spectrum, ΔE is the width of the energy bin centered at the true energy E, $T_{\text{eff}} = 1.18 \times 10^8$ s is the effective time of observation, $\Delta\Omega = 0.27$ sr is the solid angle range for the data in the analysis, $A_{\text{eff}}^{\text{H+He}}(E)$ is the effective area for H plus He elements in the experiment and $f_{\text{corr}}(E)$ is a correction factor that must be applied to $N(E)$ to compensate

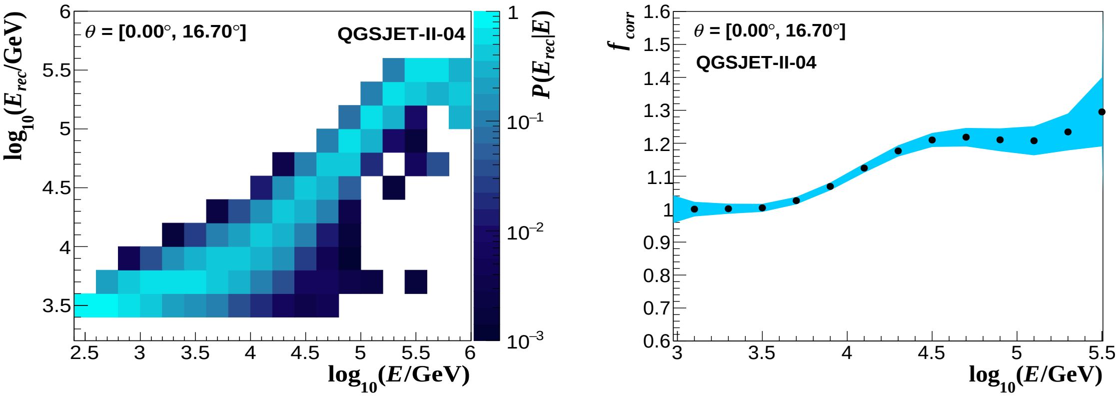

Figure 2: *Left: The detector response matrix that was employed for the unfolding procedure described in this analysis. It was generated using our MC simulations, which were produced with CORSIKA/QGSJET-II-04 and our nominal composition model of cosmic rays [5]. Right: The correction factor f_{corr} for the light mass group of cosmic rays against the true primary energy E as derived with our MC simulations. Statistical uncertainties are shown with the blue error band [5].*

Table 1: The relative statistical and systematic uncertainties on the measured energy spectrum of H+He cosmic rays at 32 TeV.

Error source	$\delta\boldsymbol{\Phi}/\boldsymbol{\Phi}(\%)$
Statistical	**±1.9**
Experimental data	±0.01
Response matrix	±1.9
Systematic	**−18.7/+11.8**
Cosmic-ray composition	−17.3/+0.9
Effective area and f_{corr}	−2.0/+1.9
Position of shower-age cut (at the curves for C and He)	−0.8/+2.9
Unfolding method (Gold's algorithm [21])	+1.2
Prior for unfolding (uniform and $E^{-1.5}$ distributions)	−1.4
Smoothing unfolding (5th degree polynomial and 353HQ-twice algorithm [22])	−1.3/+3.7
PMT efficiency and evolution of configuration	+5.0
PMT threshold	−1.5/+2.3
PMT charge	+1.8
PMT late light	−0.1/+8.8
High-energy hadronic interaction model (EPOS-LHC [23])	−6.5
Total	**−18.8/+11.9**

for the contamination of heavy primaries in the data sample of young events. Both, $f_{corr}(E)$ and $A_{eff}^{H+He}(E)$ were estimated with our MC simulations following the procedure presented in [5], they are plotted in the right and left panels of Figs. 2 and 3, respectively, versus the true primary energy. The correction factor is calculated as the inverse of the ratio between the number of H+He nuclei and the total number of events in the subsample of young EAS, while the effective area is estimated as the product of the throwing area in MC simulations, which is a circular area of 1 km radius, a geometric factor $[\cos(\theta_{max}) + \cos(\theta_{min})]/2$, and the trigger and selection efficiency for H plus He primaries.

4. Results

In the right plot of Fig. 3, we present our result for the energy spectrum of the H+He mass group of cosmic rays in the energy interval $\log_{10}(E/\mathrm{GeV}) = [3.8, 5.2]$. The statistical and systematic uncertainties are also displayed in the same figure. The magnitude of the errors rises with the primary energy. From low to high energies, the statistical uncertainty grows from ±0.8% to ±3.8%, while the systematic error goes from −12.5%/+5.3% up to −22.6%/+28.9%. A list of the statistical and systematic error sources for $\Phi(E)$ and their relative values at 32 TeV is shown in table 1.

In general, the systematic error for the intensity is dominated by uncertainties in the PMT modelling, the relative abundances of the cosmic-ray nuclei, and the high-energy hadronic interaction model, as we can see, for example, in table 1 for $E = 32$ TeV. Inside the energy interval $\log_{10}(E/\mathrm{GeV}) = [3.8, 5.2]$, the first contribution can have variations that reach up to −10.6%/+28.5%, the second one, up to −17.3%/+2.1%, and the last one, up to −10.9%/−3.7%. To evaluate the error in the spectrum due to the uncertainties in the composition of cosmic rays, we repeated the analysis using the Polygonato model [24] and three different models fitted with data from direct cosmic-ray experiments [5]. We also varied the abundance of the heavy component

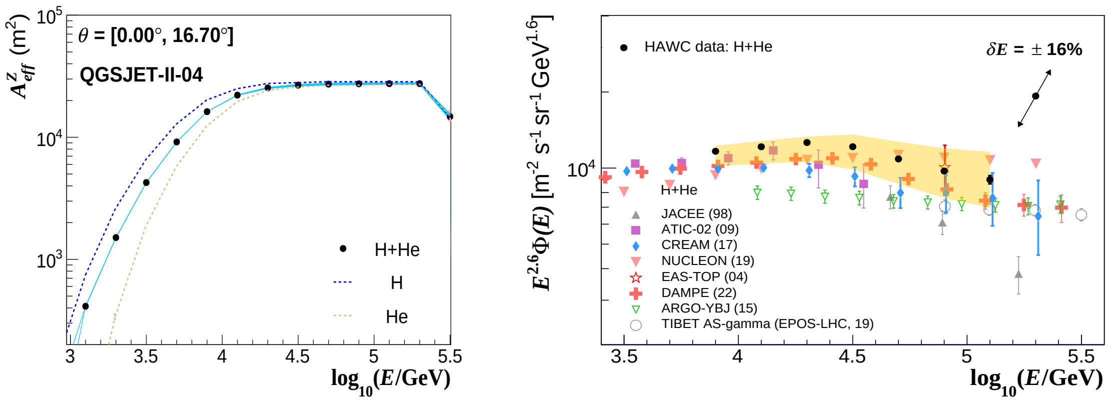

Figure 3: *Left: For the reconstruction of the energy spectrum, the effective area for H+He primaries was calculated. The result is plotted with black data points against the true energy [5]. It was derived with our MC simulations using QGSJET-II-04. For comparison, estimations for the effective area of pure H and He primaries are also shown (blue and orange dashed lines, respectively). The error band represents statistical uncertainties. Right: The HAWC energy spectrum for the H+He mass group of cosmic (black data points). Systematic errors are shown with the yellow error band, while statistical errors, with vertical error bars. We estimated that the systematic error on the HAWC spectrum implies an uncertainty on the energy scale smaller than* $\sim 16\%$*. The HAWC spectrum is compared with other measurements of the spectrum obtained with direct and indirect experiments (for a description, see section 4). The plot was updated from [5].*

in our nominal model. We evaluated the effect of the high-energy hadronic interaction model by employing EPOS-LHC [23] in the reconstruction procedure, in particular, to derive the shower-age cut and for the calculation of the response matrix and the effective area. The remaining systematic error sources contribute with an uncertainty that can reach up to $-7.0\%/+5.2\%$, when added in quadrature.

At the right panel of Fig. 3, we observe the presence of a softening at some tens of TeV in the spectrum of H+He. In order to study this feature, we fitted a broken power-law formula to the data. The expression for the fit is

$$\Phi(E) = \Phi_0 E^{\gamma_1} \left[1 + \left(\frac{E}{E_0} \right)^{\varepsilon} \right]^{(\gamma_2 - \gamma_1)/\varepsilon}, \tag{2}$$

where the free parameters are the normalization parameter Φ_0, the position of the break E_0, the smoothing parameter of the feature ε and the spectral indexes γ_1 and γ_2, which are valid before and after the break, respectively. We used a chi-squared minimization procedure for the fit and considered the statistical correlations between the unfolded data points. The best-fit parameter values are $\Phi_0 = 10^{3.71\pm0.09}\,\mathrm{m^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}}$, $\gamma_1 = -2.51 \pm 0.02$, $\gamma_2 = -2.83 \pm 0.02$, $E_0 = 10^{4.38\pm0.06}$ GeV and $\varepsilon = 9.8 \pm 4.1$, with a chi-squared value of 0.26 for two degrees of freedom. By means of a statistical analysis, we determined that the data favors the broken power-law scenario with a significance of 4.1σ over a simple power-law model.

As a systematic check of the result, we used an alternative shower-age cut that was obtained by maximizing the purity of the subsample, specifically the quality factor [25], inside each E_{rec} bin with the restriction that we should also keep at least 50% of each primary nuclei in the data subset. The spectrum obtained in this manner maintained a similar shape than the one that was reconstructed with our standard method, but it was softer above 20 TeV (γ_2 is reduced by 4.9%). We also confirmed our result by unfolding the light and heavy ($Z > 2$) mass groups of cosmic rays from the data on the shower age vs the primary energy of EAS [6]. In conclusion, we found a robust result for the spectrum.

A compilation of different measurements of the H+He spectrum of cosmic rays is presented in the right-hand side of Fig. 3 together with the HAWC spectrum. We also show results from the direct experiments CREAM I-III [7], JACEE [26], ATIC-2 [27], NUCLEON [28] and DAMPE [29], and from the EAS detectors EAS-TOP [30], ARGO-YBJ [31] and Tibet AS-gamma [32]. Within systematic uncertainties, the HAWC spectrum is in agreement with the ATIC-2 data between 6 and 25 TeV and with NUCLEON results in the interval from 16 to 158 TeV. On the other hand, in general, we observe that HAWC data tend to be above the measurements of CREAM I-III, JACEE, ARGO-YBJ and Tibet AS-gamma. At around 80 TeV, HAWC overlaps with the EAS-TOP data point.

5. Discussion

The results of the present analysis confirm the presence of a break at tens of TeV in the energy spectrum of H+He cosmic-ray nuclei. The existence of this structure was first hinted by the balloon-borne experiments CREAM I-III [7] and ATIC-2 [27], and later by the NUCLEON space detector [28]. Recent measurements with the satellite experiment DAMPE also reveal the presence of this feature [29]. There are, however, differences among the intensities of the spectra from these experiments, which could be ascribed to the effect of experimental systematic errors. Albeit, it is remarkable that EAS experiments based on Cherenkov techniques can provide similar conclusions about the composition of cosmic rays to those from direct detectors. These results seem to rule out the possibility that the spectrum has a simple power-law behaviour in the $10-100$ TeV energy region as implied by the measurements from ARGO-YBJ [31]. The existence of a break in the spectrum of proton plus helium nuclei at tens of TeV has interesting implications for the physics of cosmic-rays. For example, it may imply the presence of nearby TeV cosmic-ray accelerators at distances of the order of 100 Mpc from Earth [33] or the existence of a new population of cosmic-ray sources [34].

6. Conclusions

Using the HAWC observatory, we have measured the cosmic-ray energy spectrum of H+He nuclei for energies between 6 and 158 TeV. Our measurements confirm the presence of a softening in the spectrum at tens of TeV, as it was previously suggested by the ATIC-2, CREAM I-III and the NUCLEON experiments, and recently corroborated by the DAMPE data. By means of a statistical analysis, we found that the break of the spectrum is located at $24.0^{+3.6}_{-3.1}$ TeV and has a statistical significance of around $4.1\,\sigma$ in our data. This measurement demonstrates that high-altitude water Cherenkov observatories can also be used to study the composition of cosmic-rays at TeV energies and hence to complement the observations from direct detectors in this energy regime.

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