The Knee of the cosmic hydrogen and helium spectrum below 1 PeV measured by ARGO-YBJ and a Cherenkov telescope of LHAASO (Postprint)

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Abstract

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Full Text

The Knee of the Cosmic Hydrogen and Helium Spectrum below 1 PeV Measured by ARGO-YBJ and a Cherenkov Telescope of LHAASO

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Abstract

The measurement of cosmic ray energy spectra, in particular for individual species, is an essential approach in finding their origin. Locating the "knees" of the spectra is an important part of this approach and has yet to be achieved. Here we report a measurement of the mixed Hydrogen and Helium spectrum using the combination of the ARGO-YBJ experiment and a prototype Cherenkov telescope for the LHAASO experiment. A knee feature at 640 ± 87 TeV, with a clear steepening of the spectrum, is observed. This provides fundamental inputs to galactic cosmic ray acceleration models.

Keywords: Cherenkov telescope; ARGO-YBJ; energy spectrum; hybrid measurement; composition.

Introduction

Galactic cosmic rays are believed to originate from astrophysical sources such as supernova remnants. The mechanism for accelerating nuclei to energies from 10^{14} eV to 10^{20} eV remains unknown. A handful of significant structures in the approximately power-law spectrum occur across the entire energy range. One of them is a significant downward bending of the spectrum around 3×10^{15} eV, the so-called "knee" . Many acceleration models have successfully explained the power-law characteristics of the spectrum, although no originating source has yet been experimentally observed for the high-energy particles. The knee of the spectrum obviously plays a key role in testing proposed acceleration and propagation models. One theory is that the knee marks the highest energy that galactic cosmic ray sources can reach. The spectrum of all cosmic rays, however, does not appear to bend sharply, because different species may have different cut-off energies and extra-galactic cosmic rays may merge into the flux, potentially dominating at higher energies.

Such a straightforward investigation has unfortunately been very difficult in past decades due to two experimental limitations. First, precision measurement of cosmic ray species and energies with space or balloon-borne calorimeters and charge-sensitive detectors has been constrained by their small exposure due to limited payload, so that statistically reliable measurements cannot effectively extend to energies higher than 10^{14} eV, far below the knee. Second, ground-based experiments using extensive air shower (EAS) techniques suffer from large uncertainties such as unknown energy scale and lack of effective tools to tag the nature of the primary particle inducing the observed showers, independent of the statistical accuracy of the measurement. As a consequence, different experiments find different knee energies, as summarized in FIG. 1 [Figure 1: see original paper] of reference, mainly because of the unknown mixture. The uncertainty in attempts to measure the pure proton spectrum is still large; for example, the knee is found at a few hundred TeV in CASA-MIA and at a few PeV in KASCADE. The lack of well-measured knee energies for individual species is prohibitive for developing a precise theory about the origin of cosmic rays.

The situation is improved by the ARGO-YBJ experiment, located at 4300 m above sea level in Tibet, which records nearly every secondary charged particle of showers incident upon its unique detector made of a continuous array of Resistive Plate Chambers (RPC). Such a setup brings the threshold of shower measurement by ARGO-YBJ down to the same energy range as CREAM. This enables ARGO-YBJ to establish the energy scale by measuring the moon shadow and cross-checking with CREAM. This improvement is enhanced with the addition of data from a Cherenkov telescope imaging every shower in its field-of-view (FoV). The hybrid combination of the two techniques improves the resolution for shower energy measurements and enhances the capability to discriminate showers induced by Hydrogen and Helium nuclei (H&He) from events initiated by heavier nuclei. Here, we report the measurement of the knee of the energy spectrum of the light component (H&He) below 1 PeV using hybrid data from the ARGO-YBJ RPC array and the Cherenkov telescope, which is a prototype of one of the main instruments in the future LHAASO experiment.

The Hybrid Experiment

The hybrid experimental data set includes air showers whose cores fall within an area of $76\,\text{m} \times 72\,\text{m}$ fully covered by the ARGO-YBJ RPC array (i.e., within 1 m from the edges of the array) and whose arrival directions lie within the effective FoV of the telescope—a cone of 6° with respect to the main axis of the telescope, which has a full FoV of $14^\circ \times 16^\circ$ pointing 30° from the zenith. The telescope is positioned about 79 m off the center of the array in the southeast direction, defining a geometrical aperture of $163\,\text{m}^2\text{sr}$.

According to simulations of the hybrid experiment, high-energy ($\geq$ 100 TeV) showers are detected with almost full efficiency, particularly H&He events. This minimizes the uncertainty of the cosmic ray flux measurement. Within its FoV, the telescope has an array of 256 pixels, each approximately one square degree in size. The shower image records the accumulated Cherenkov photons produced throughout the entire shower development. As described below, the total number of photons in the image can be used to reconstruct the shower energy, while the image shape indicates the depth of shower development after reaching its maximum, providing useful information for selecting proton or Helium showers.

The ARGO-YBJ array consists of 1836 RPCs, each equipped with two analog readout "Big Pads" ($140\,\text{cm} \times 123\,\text{cm}$) to collect the total charge induced by particles passing through the chamber. The collected charge is calibrated to be proportional to the number of charged particles. The most hit RPC, together with surrounding RPCs, measures the lateral distribution of secondary particles within 5 m from the core. This unique measurement is very useful not only for precise reconstruction of shower geometry but also for selecting proton and Helium showers.

The coincident cosmic ray data collected in the hybrid experiment from December 2010 to February 2012 are used for the analysis presented in this paper. The main constraint on the exposure of the hybrid experiment is the weather condition during moonless nights. Weather is monitored using bright stars in the FoV of the telescope and an infrared camera covering the whole sky. More details about the criteria for good weather can be found elsewhere. Combining good weather conditions with the live time of the RPC array, the total exposure time is 7.28×10^5 seconds for the hybrid measurement. Additional criteria (quality cuts) for well-reconstructed showers in the aperture of the hybrid experiment are: (1) at least 1000 particles recorded by the ARGO-YBJ digital readout to guarantee high-quality reconstruction of shower geometry; and (2) at least 6 pixels triggered in each shower image. About 32,700 events survive these cuts, among which 8218 high-energy events above approximately 100 TeV are detected. The core and angular resolutions are better than 1.2 m and 0.3°, respectively.

A large sample of extensive air showers, including their Cherenkov photons, is simulated using the CORSIKA code with the high-energy hadronic interaction model QGSJETII-03 and the low-energy model GHEISHA. The G4argo package and a ray-tracing procedure on the Cherenkov photons are applied for further simulation of detector responses. All five mass groups—proton, Helium, C-N-O group, Mg-Al-Si group, and Iron—are generated in the simulation. A detailed comparison between data and simulation can be found elsewhere.

Shower Energy Reconstruction and All-Particle Distribution

The shower energy, E, is reconstructed using the total number of Cherenkov photo-electrons, N_{pe}, collected by the telescope observing the shower with a certain impact parameter R_p, as determined by the shower geometry. Using a very large sample generated by the simulation described above, a look-up table for shower energy with two entries—N_{pe} and R_p—is determined for each mass group. For a shower with N_{pe} measured by the telescope and R_p measured by the RPC array, the shower energy can be read from this table. The energy resolution is found to be symmetric and fits well a Gaussian function with σ between 23% and 27% for different mass groups. However, a clear feature of the energy reconstruction is a systematic shift that depends on the nature of the primary. Around 1 PeV, the difference between proton and Iron showers is approximately 37%, significantly greater than the resolution. For a mixed sample with unknown composition, this feature will distort the all-particle energy spectrum even if the measurement is fully efficient, namely with a constant geometrical aperture independent of energy.

To compare with other experiments or existing cosmic ray flux models without assuming any specific mixture of species for the measured showers, in FIG. 1 [Figure 1: see original paper] we plot the event distribution as a function of the measured number of photo-electrons N_{pe}. Also plotted are distributions generated according to the all-particle spectra measured by experiments and the corresponding assumptions on the mixture of different species. Here we show results from Tibet ASγ with two different composition models, from KASCADE with its composition models obtained from unfolding procedures, and two widely quoted composition models—Hörandeland and H4a. The corresponding energy range is from 126 TeV to 15.8 PeV assuming a 1:1 mixture of proton and Helium showers. The comparison shows that existing all-particle spectra and their corresponding composition models are in general agreement at the 30% level. The data used in this work also maintain general agreement with others at a similar level.

Hydrogen and Helium Event Selection

Secondary particles in showers induced by heavy nuclei are spread further away from the core region. Therefore, significant differences in lateral distributions exist near the cores between showers induced by light or heavy nuclei. Beyond a certain distance (e.g., 20 m from the core), the lateral distributions become similar because they are mainly due to multiple Coulomb scattering of secondary particles and are well described by the Nishimura-Kamata-Greisen (NKG) function. With its full coverage, the ARGO-YBJ array uniquely measures the lateral distribution of secondary particle density at the shower core. The number of particles recorded by the most hit RPC in an event, denoted as N_{max}, is a good parameter to discriminate between showers with different lateral distributions within 3 m from the cores. For a shower induced by a heavy nucleus, N_{max} is expected to be smaller than that in a shower induced by a light nucleus with the same energy. Obviously, N_{max} depends on the shower size, which can be indicated by N_{pe} at distance R_p from the shower axis. We define a reduced dimensionless variable $p_L = \log_{10} N_{max} - 1.44 \log_{10} N_{pe} - R_p/81.3\,\mathrm{m} + 3.3$, empirically obtained from MC simulation, to absorb the shower size effect.

The shape of the shower image recorded by the Cherenkov telescope is also a mass-sensitive parameter. The elliptical image is described by Hillas parameters such as width and length. Images are more stretched (i.e., narrower and longer) for showers that develop more deeply in the atmosphere. The length-to-width ratio (L/W) is therefore sensitive to the depth of shower maximum, which depends on the nature of the primary. It is also known that images are more elongated for showers farther from the telescope due to purely geometric reasons. The ratio L/W is nearly proportional to the shower impact parameter R_p but depends only moderately on shower size. Taking into account the dependence on measured number of Cherenkov photons and impact parameter, we define a reduced dimensionless variable $p_C = L/W - R_p/97.2\,\mathrm{m} - 0.14\log_{10} N_{pe} + 0.32$, obtained again from MC simulation, to absorb both R_p and shower size effects.

Selection of the H&He sample is carried out by combining the two composition-sensitive parameters. A correlation analysis shows that the two variables are quite independent, with composition groups significantly separated in the p_L-p_C map. This map can be plotted with probability contours for the two mass groups—H&He and heavier nuclei (FIG. 2 [Figure 2: see original paper]). The cuts $p_L \geq -1.23$ or $p_C \geq 1.1$ result in a selected sample of H&He showers with a purity of 93% below 700 TeV and an efficiency of 72%, assuming the composition models given in references. The aperture gradually increases to $120\,\mathrm{m}^2\mathrm{sr}$ at 300 TeV and remains constant at higher energies. The contamination from heavier nuclei increases with energy, becoming about 13% around 1 PeV and gradually rising to 45% around 6.5 PeV. This contamination obviously depends on the composition assumption, and the associated uncertainty is discussed below.

Energy Spectrum of Proton and Helium

The energy spectrum of the selected H&He shower sample is plotted in FIG. 3 [Figure 3: see original paper]. The shower energy is now better defined because the intrinsic scale difference between H and He showers is smaller than 10%, significantly lower than the energy resolution. Using approximately 40,000 simulated events that survive all reconstruction quality cuts and H&He selection, the energy resolution function is found to be Gaussian with a constant standard deviation of 25% and overall systematic shift less than 2% at energies above 100 TeV. To account for energy resolution and any smearing such as bin-to-bin migration from true to reconstructed primary energy, a Bayesian algorithm is applied to unfold the observational data. The selection efficiency for He showers is approximately 80% of that for H showers. Contamination due to heavy nuclei is subtracted in each bin considering the composition model from reference.

Systematic uncertainties arise mainly from the following sources: (1) Assumptions on the flux of heavy species. Below 800 TeV, a flux uncertainty of 1.9% is estimated by considering the models in references and extrapolation from CREAM data. Above 800 TeV, this uncertainty increases with energy up to 23.3% at 2.5 PeV. (2) Due to slightly different detection efficiencies for H and He showers, the fraction of Helium in the selected samples depends on composition assumptions, resulting in a 3% uncertainty in overall flux. (3) Choice of interaction models. The overall flux uncertainty is about 4.2% when considering high-energy interaction models SIBYLL and QGSJET, and low-energy interaction models GHEISHA and FLUKA. (4) Boundary effects of the aperture. Boundaries were slightly varied to smaller RPC array and smaller telescope FoV, with corresponding flux uncertainty of about 3% indicated by deviation from linear response to variation. (5) Calibration for the number of particles measured by RPCs. Depending on calibration methods, we find a 7% uncertainty in the number of events surviving all criteria involving RPC response. The overall systematic uncertainty on the flux is plotted as the shaded area in FIG. 3.

A more stringent cut for higher purity (97%) H&He sample has been applied below 700 TeV, where the spectrum fits well with a single-index power law according to CREAM and ARGO-YBJ. This yields a much smaller but constant aperture of $\sim 50\,\mathrm{m}^2\mathrm{sr}$ above 250 TeV, negligible contamination from heavy nuclei, and a corresponding precise measurement of the spectrum, shown by filled squares in FIG. 3. This serves as verification for both energy scale and absolute flux when compared with previous measurements. Differences between fluxes measured by these experiments are found to be less than 9%.

Discussion and Conclusions

An evident bending structure is observed in the cosmic H&He spectrum by the hybrid experiment using the ARGO-YBJ RPC array and the imaging Cherenkov telescope at 4300 m above sea level. Previous measurements below 700 TeV indicate that the spectrum follows a single power law with index -2.62. Beyond 3 PeV, however, many experiments report an evident bending in the all-particle spectrum, although with a spread in bending energy. With normalization factor $J_0 = (1.82 \pm 0.16) \times 10^{-11}\,\mathrm{GeV}^{-1}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ at 400 TeV, the four flux values measured below 700 TeV are well fitted by a single-index power law. Together with its extrapolation up to 3160 TeV (the upper boundary of the last bin in our analysis), this power-law spectrum has been used as the a priori expectation.

The significance of deviation of the bent spectrum from the single-index power law is measured by calculating the chance probability. In the range from 800 TeV to 2000 TeV, 85 events are observed, compared to an expectation of 118 events derived from the hypothetical spectrum plus contaminating heavy species. From 2000 TeV to 3160 TeV, 9 events are observed versus an expectation of 22. This corresponds to a deviation of 4.4σ. A broken power law fits the measured spectrum well. Below a break energy E_k, the assumed spectrum describes the data very well with $\chi^2/\mathrm{dof} = 0.7$ for the first four points. Above the break, the data can be fitted by $J_0 \cdot (E_k/400\,\mathrm{TeV})^{-2.62} \cdot (E/E_k)^{\beta}$, with $E_k = 640 \pm 87$ TeV and $\beta = -3.34 \pm 0.28$. The relatively large error on E_k is due to limited statistics and finite energy resolution. Additionally, the systematic error in the energy scale is 9.7%, which corresponds to ~ 62 TeV at E_k.

In summary, the joint operation of the ARGO-YBJ detector with a wide field-of-view and imaging Cherenkov telescope allowed detailed investigation of the energy range bridging the gap between direct observations by CREAM and the ground-based KASCADE experiment. This hybrid experiment yields clear evidence for a knee-like structure in the spectrum of light primaries (protons and Helium nuclei) below 1 PeV. Observation of the knee of the primary light component at such a low energy provides fundamental inputs to galactic cosmic ray acceleration models.

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FIG. 1. Distribution of the number of Cherenkov photo-electrons measured by the telescope (filled circles) with a bin width of 0.22 in $\log_{10} N_{pe}$. The histograms represent distributions generated according to flux models and all-particle spectra and corresponding composition models obtained from Tibet ASγ and KASCADE experiments.

FIG. 2. Composition-sensitive parameters p_L and p_C for the two mass groups, H&He (solid contours) and heavier components (dashed contours). The numbers on contour isolines indicate the percentage of contained events.

FIG. 3. H&He spectrum from the hybrid experiment with ARGO-YBJ and the imaging Cherenkov telescope. A clear knee structure is observed. The dashed line represents the fit to the data. The single-index spectrum below 700 TeV and its extrapolation up to 3160 TeV (solid line) was used as an a priori assumption. The H&He spectra from CREAM, ARGO-YBJ, and the hybrid experiment below the knee, and spectra from Tibet ASγ and KASCADE above the knee are shown for comparison. Shaded areas represent systematic uncertainty.

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