Measurement of knees of the spectra of heavy nuclei above 10 PeV with LHAASO

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Abstract. Measuring the knees of the cosmic ray spectra for individual species is a very important approach to solve the problem of the origin of ultra high energy galactic cosmic rays. The knee of the iron spectrum is implied to be above 10 PeV from previous experiments, such as ARGO-YBJ and LHAASO-WFCTA. LHAASO is a suitable size for measurements with the required precision. The key is to separate iron nuclei from all cosmic ray samples. In this paper, we identify a couple of variables that are sensitive to the composition of showers recorded by the detector arrays in LHAASO. A multi variate analysis is proposed for the separation. The efficiency and purity of the selection for demanded species are optimized by well configuring the LHAASO array using the LHAASO simulation tools.

1 Introduction

The most significant feature of the power-law-like spectrum of Cosmic Rays (CR) with all mixed species is the “knee”, i.e. a significant bending of the spectrum from the power-law index of approximately -2.7 to -3.1 around a few PeV. The origin of the knee still remains a mystery since it was discovered. Disclosing the mechanism of the knee would be a significant improvement in understanding the origin of the galactic cosmic rays. Measuring the knees for every single species will be a significant progress towards the goal. At an altitude of 4300 *m* above sea level, the ARGO-YBJ resistive plate chamber (RPC) array and air Cherenkov telescopes were combined to carry out the experiment [1] and resulted in a clean measurement of the spectrum of CR protons and α 's over the range from 100 TeV to 3 PeV and the discovery of a knee in the spectrum at 0.7 PeV, which is well below the knee of the all particle spectrum [2]. According to plausible assumptions of the bending being due to either rigidity (*Z*) or total number of nucleus (*A*) dependent, the knee of the iron spectrum will be around either 18 PeV or 39 PeV. A precise measurement of the knee of the iron spectrum is obviously very important to understand the mechanism of the knee. However, the composition measurement in the energy range above 10 PeV is really difficult because a rather large detector array is required due to the very low flux. Moreover, a multi-parameter measurement is also required to maintain a high resolution in the shower composition by providing sufficient information about the showers in identifying their composition. A high energy resolution is also essential to find the knee structure and its energy. Therefore,

such a measurement has not been achieved so far. The Large High Altitude Air Shower Observatory (LHAASO) [3] having many components of detector arrays, may enable the measurement with a sizable array to guarantee the required collection of shower samples and the resolutions in both composition and energy of shower detection. In this paper, we describe the LHAASO detector arrays that are relevant to the measurement in the second section, identify the parameters measured by LHAASO that are sensitive to the composition, and the selection of iron samples out of all shower events in the third section and report the preliminary results on the expectation of the spectrum measurement using the LHAASO simulation kit in the summary section.

2 Detector Arrays in LHAASO

2.1 Scintillator Counter Array and Muon Detector Array

The major component of LHAASO is an array of 5195 scintillator counters with a spacing of 15 *m* between any two counters. Each counter is composed of 1 *m*² of scintillator plates, wave length shifting fibers embedded in the plates and a Photo Multiplier Tube (PMT) with a circular photo-cathode of 38 *mm* in diameter. The scintillating light in the plates induced by particles passing through the counter is collected and guided to the PMT by the fiber bundle. With a timing resolution better than 2 *ns* [4], the PMT times the arrival moment of the particles as a *hit* with an absolute time stamp distributed from the data center through a fiber network covering the entire array. The White Rabbit Protocol (WRP) [5] is running in the network which is connected with special switches for WRP

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and synchronizes all clocks at the counters within 200 ps. The total charge of the *hit* proportional to the number of particles passing through the counter is digitized at the counter with a resolution of 25% for a single particle or 5% for 10,000 particles, respectively. In order to catch 90% of the shower particles, namely γ 's, a 5 mm sheet of lead is installed on top of the scintillator plate to convert the γ 's into pairs of electrons and positrons. This significantly improves the shower arrival direction and shower core position resolution. Both timing and charge signals are transferred through the network upwards to the data center where a trigger of the shower event is formed if any 6 hits in any area with a radius of 100 m are coincident in a window of 300 ns [6].

A shower above 10 PeV typically generates more than 500 hits in the array. They allow a reliable reconstruction of the shower front and result in a shower arrival direction with a resolution better than 0.3° . The number of particles in the counters measures the shower lateral distribution very well and result in a shower core location with a resolution of 4 m. The array of 1.0 km^2 is surrounded by an outer ring composed of 294 counters with a spacing of 30 m to identify showers that have their core located outside the array and reject them in the reconstruction.

The shower muon-content is measured in LHAASO by using the muon detector (MD) array of 1171 water Cherenkov muon counters with a spacing of 30 m and covering an area of 1.0 km^2 . Each MD is a cylinder, with a diameter of 6.8 m and height of 1.2 m, filled with pure water. The inside layer of the liner in MD is a highly reflective material, *i.e.* TYVEK film. An 8" PMT is installed at the center on top of the liner, looking down into the water through a transparent window. Muons passing through water generate Cherenkov light which bounces back and forth on the surface of the TYVEK until it reaches the cathode of the PMTs. The detection efficiency of muons that fall inside the area of the counter is around 97% throughout the whole detector, with a threshold of 1/4 height of a single muon pulse in the detector [7]. In order to screen the electrons and photons in showers, MDs are covered by dirt with a depth of 2.8 m. This results in a very clean measurement of muons above 1 GeV, except one or two counters being hit right on by the shower cores. Those counters could be polluted by the energetic electrons or photons typically in the shower cores and could be saturated as well. Therefore, they will be eliminated in shower reconstruction.

The pulse waveform of a MD is read out by using 500 MHz flash ADC once the signal is over the threshold with a linear charge response over a dynamic range from 1 to 10,000 muons. The non-linearity is less than 5%. Each pulse is timed by using the absolute time stamp distributed through the WR network with a resolution of 2 ns. Only the integral of the waveform, which is proportional to the total charge from the PMT, and the time stamp are collected at the farm in the data center. Using a single muon signal, the total charge is calibrated as the number of muons falling into the counter. The resolution is 25% for a single muon and 5% for 10,000 muons, respectively. Once a shower event is formed using the scintillator counter ar-

Figure 1. The layout of the scintillator counter (small dots) array, muon counter (big dots) array, water Cherenkov detector (rectangle in the center) array and the location of the wide field of view (FoV) Cherenkov telescope (small squares) array in the LHAASO experiment (upper panel). The FoV of the telescopes in the entire northern sky map (lower panel). The azimuth angle 90° is the north direction. Curves in the sky indicate the trajectories of the moon in one year.

ray, the number of muons at all MDs within a window of 100 ns are included in the event. Respecting the shower core determined by the scintillator counter array, the lateral distribution of the muons is well measured. Integrating the distribution over the whole array, the muon content of the shower is calculated.

2.2 SiPM Staffed Cherenkov Telescope Array and Its Configuration

18 Cherenkov telescopes are arranged as much as possible in the central region of the scintillator counter and the MD array to maximize the utilization of the whole area of 1.3 km^2 as illustrated in Figure 1. For shower energies above 10 PeV, the telescopes are fully efficient in the areas with the shower impact parameter $R_p \leq 400 \text{ m}$ with the trigger criteria of at least 6 registered pixels and each pixel having at least 10 photo-electrons (*P.E.*'s). The main axes of all telescopes are arranged at an elevation of 45° , therefore the field of view (FoV) of the 18 telescopes covers a ring of the sky with a width of 16° in elevation and full circle of 360° in azimuth at an elevation of 37° which is the lower edge of the ring. At the higher edge of the ring, elevation of 53° , there is an overlap of about 13 pixels between the adjacent telescopes. The FoV is also shown in Figure 1, in the lower panel.

A major upgrade has been made on the design of the telescope, compared to its prototype [8]. The aluminized

Figure 2. The wavelength response function of relevant components of the telescope including mirrors, filter, Winston cones and the SiPMs. The response of the cones is an average over all incident angles. The overall response function is also shown.

spherical reflecting area of 5 m^2 as the light collector remains as for the prototype, but the telescope now can be tilted up and down in elevation from 0° to 90° with an improved support system. At the focal plane, 2870 mm away from the mirror center, a camera with 1024 square pixels, instead of 256 hexagonal ones, is redesigned to image the shower in its FoV of $16^\circ \times 16^\circ$. The pixel, with a FoV of $0.5^\circ \times 0.5^\circ$, is formed of $1.5 \text{ cm} \times 1.5 \text{ cm}$ SiPM receiving photons reflected by the mirror through a Winston cone. Both entrance and exit pupils of the cone are square shaped with an area ratio of 2.65. The internal reflective surface is aluminized with a reflectivity ranging from 89% to 97% depending on the incident angle. The largest receiving angle is about 35° with respect to the normal vector of the SiPM active surface for photons reflected from the edge of the mirror. The overall collecting efficiency of the cone is 93% without counting the blind gaps between the cones due to their thickness. The SiPM is an array of 0.56 million avalanche photo diodes (APD) with a size of $20 \mu\text{m}$. The diode is working in the Geiger mode allowing the whole pixel to have a dynamic range from 10 to 40,000 *P.E.*'s with a non-linearity less than 5% [9]. In front of the cones and SiPMs, a wide-band filter is installed to suppress the incident light above 550 nm in which bandwidth the night background light (NBL) is mainly distributed. This is the way to enhance the signal to noise ratio. The overall working wavelength range of the telescope is from 300 nm to 550 nm including the contribution from the mirrors, filters, Winston cones and SiPMs. The peak at 460 nm is mainly due to the quantum efficiency of SiPMs, which is about 30% at the peak. The overall response function in wavelength, taking into account the complex angular response of the cones, is shown in Figure 2.

16 pixels form a cluster, which can be removed and replaced easily from the camera, with the front end electronics (FEE) and the digitization of the waveform integrated together. The waveform, typically 120 ns wide, is digitized with a sampling rate of every 20 ns by using two 50 MHz 12-bit flash ADC's at high gain and low gain channels to cover the whole dynamic range of the SiPM's. The ratio of gains between the two is 7:1. The high gain chan-

nel has its own background fluctuation (σ) measurement and corresponding trigger threshold setting, e.g. 4σ within a window of 240 ns . Once it is triggered, a signal, T_0 , will be generated and transmitted to the trigger logic that collects all the signals from all 1024 pixels. The trigger logic is installed on the back board of the camera. A pattern recognition algorithm is operated to decide whether or not a shower has been observed and generate a signal, T_1 , to every channels in all telescopes in the array. The waveform data are read out from each channel and integrated for the total charge measurement. Simultaneously, an average time weighted by the amplitude is calculated for timing measurement in each pixel. Both charge and timing data are transmitted to the data center with the absolute time stamp distributed through the WR network which also allows the data being transmitted upwards to the data center from each telescope.

Figure 3 shows a complete shower event of a 20 PeV iron nucleus as an example by the maps of hits in the scintillator, muon counter array and the Cherenkov image in the cameras. The spots located at the position of the counters indicate the hit with the radius of the spot proportional to the logarithm of the number of particles, the color (gray degree in black/white version) of the spot indicates the timing of the hit. The shower core is clearly measured in the array. In the lower panel, the shower Cherenkov image is recorded by the array of telescopes. The color (or gray degrees) of registered pixels indicate the number of *P.E.*'s. According to the shower geometry determined by the scintillator counter array, the R_p is 200 m .

In the lower panel of Figure 1, which shows the FoV of the telescope arrays in the sky, curves in dashed lines on both sides of the panel indicate the transient trajectories of the moon in the entire year. Since the aging effect of SiPMs is negligible and their operating threshold is higher than the NBL fluctuation even with the full moon, the telescopes are able to be operated in all dark periods except those directly looking at the moon. By timely switching off those telescopes and keeping all others on, one could significantly increase the observational time. In average, 17 telescopes out of 18 have a duty cycle as high as 30%, which is essentially the whole dark period between twilight with or without the moon in the sky. To measure the quite low flux of cosmic rays in such a high energy range above 10 PeV , this is very necessary for the hybrid measurement with the 1.3 km^2 ground array.

3 Composition sensitive parameters and their measurements

As described above, LHAASO measures the lateral distributions of muons in EAS and ordinary particles, γ 's and e^+e^- . This allows the calculations of both total number of muons N_μ^A , where A indicates the atomic number of the primary particle of the shower, and the size N_{tot} of the shower. Since the muon content in a shower is a simple power law as a function of the shower energy, so $N_\mu^A/N_\mu^p \approx A^{(1-\eta)}$, where η is the index of the power law and is far away from 1, and p indicates the proton shower,

Figure 3. A 20 PeV iron shower event hit in the array with the $R_p \sim 200m$ to the telescopes. The registered scintillator counter map and muon counter map are shown in the upper and middle panels, respectively. The image of the shower taken by the telescopes is shown in the bottom panel. The ‘cross’ mark in this panel indicates the arrival direction of the event determined by the scintillator array.

is almost the most sensitive parameter to the shower composition. Usually, the reduced muon content N_μ/N_{tot} , denoted as C_μ , is used in selecting showers with a specific composition. In Figure 4, distributions of the inverted muon content ($1/C_\mu$) for iron showers are plotted to compare with the same distribution of all other showers, with the assumption that every group of species, *i.e.* iron, Mg-Al-Si, C-N-O, Helium and proton, are evenly distributed and independent of the shower energy. The separation is quite clear. The same comparisons between the distributions are plotted for some more realistic assumptions about the composition in Figure 4 [10].

Telescopes take the Cherenkov images of the showers in their FoV. For 10 PeV and higher energies, the shower

Figure 4. Distributions of inverted muon contents ($1/C_\mu$) in showers with 5 groups of species, *i.e.* iron (in pink), Mg-Al-Si (blue), C-N-O (green), Helium (red) and proton (black). Upper, events are evenly distributed among 5 species; Lower, with the assumption of composition in [10]

image is very bright and the number of registered pixels is typically greater than 100 even for showers with $R_p \sim 400m$. Given the shower distance using the shower geometry reconstructed by the scintillator counter array, the total number of photons in the image measures the shower energy. See below for a detailed discussion on the shower energy reconstruction. The angular offset of the shower image from the arrival direction measures the height of the shower maximum, measured by the vertical atmospheric depth X_{max} with a resolution of $\sim 50 g/cm^2$. Figure 5 shows the relationship between X_{max} and the angular offset. The resolution is rather sensitive to how well the shower image is contained in the FoV of the telescopes. In order to achieve a selection for the well imaged showers, the total number of registered pixels, N_{pixel} , and the angular distance from the shower arrival direction to the upper and lower boundary of the FoV, Y , are required to be $N_{pixel} > 100$ and $|Y| > 1^\circ$, hence images with most part falling outside the FoV will be eliminated. Measuring the shower X_{max} is the traditional method of primary particle identification in calorimeter detection of showers, such as air fluorescence or Cherenkov light detection of showers. Due to the well known elongation of showers in the air, *i.e.* X_{max} is proportional to $\log E$, where E is the shower energy, $X_{max}^{(p)} - X_{max}^{(A)} \propto \log A$, A is the atomic number of the primary nucleus and p indicates primary proton. As a comparison,

Figure 5. Relationship between vertical X_{max} and the angular offset of the centroid of the shower image from the arrival direction (upper) and corresponding resolution of X_{max} (lower). In the lower panel, the solid curve is the resolution function of showers that have impact parameter $R_p < 200m$ and the dashed curve is for $R_p > 200m$, respectively

the typical resolution of X_{max} for a fluorescence light experiment is about $25 g/cm^2$ if the shower profile is well contained in the FoV of the telescope array. In Figure 6, the distribution of the reconstructed X_{max} for iron showers is plotted to compare with the same distribution for all other showers, assuming the 5 groups of species are evenly distributed and independent of the shower energy. The resolution of the Cherenkov telescopes has been taken into account. Also shown in Figure 6, the same comparison between the distributions are plotted for some more realistic assumptions about the composition [10].

A one-to-one correlation between the parameters, the inverted muon content, $1/C_\mu$, and shower maximum, X_{max} , have been checked by plotting them in the scatter map in Figure 7. They are found to be quite independent with the correlation coefficient less than 90%. In this map, 5 group of species are plotted in different colors and the iron showers are clearly outstanding in the lower-left corner from other species. With a simple cut, $1/C_\mu < 6$ & $X_{max} < 460 g/cm^2$, one can achieve the selection of the pure iron showers out of all well constructed CR samples with a certain purity of 70% at 10 PeV to 85% at 100 PeV . The effective aperture of the detection of the iron showers is about $3.4 \times 10^5 m^2 sr$. This results a collection of about 16,000 iron showers above 10 PeV per year according to

Figure 6. Distributions of vertical X_{max} of showers with 5 groups of species, i.e. iron (in pink), Mg-Al-Si (blue), C-N-O (green), Helium (red) and proton (black). Upper, events are evenly distributed among 5 groups of species; Lower, with the assumption of composition in [10].

an assumption of the spectra of the 5 groups of species with corresponding knees [10] and about 164 iron showers in the last bin near 100 PeV . The expected spectrum is shown in Figure 8 as the solid squares. The knee, if it is there, will be discovered with high significance in a one year operation of the hybrid observation using the LHAASO instruments.

Given a single composition sample of CRs with a purity of 75% or better, the energy reconstruction of the shower is rather straightforward by using the total number of Cherenkov photons in the shower image. This minimizes the uncertainty due to the unknown composition. The total number of photons has been proved to be a good energy estimator because the resolution function is a symmetric Gaussian with a bias less the 5%. This is a good feature of the Cherenkov technique in the power-law-like spectrum measurement with minimized distortion. Another good feature of the technique is that the energy resolution is almost a constant of less than 20% over a wide energy range. This is very important in finding the structures of the spectrum if there is such a knee. Every part of the spectrum is equally measured with the consistent resolution.

To separate the mixed iron and Mg, Al, Si nuclei out of all events is an easier job with a purity better than 70% and even 90% around 100 PeV . The gain is that the effective aperture increases, and reaches $4.2 \times 10^5 m^2 sr$ due to relax-

Figure 7. The correlation between $1/C_\mu$ & X_{max} for 5 groups of species of iron (in pink), Mg-Al-Si (blue), C-N-O (green), Helium (red) and proton (black). The cuts indicated by the solid and dotted lines can be applied to select the iron samples and a mixed heavy nuclear group out of all events, respectively.

Figure 8. The expectation of the spectra of pure iron and the mixed heavy nuclear group, respectively, over an energy range from 10 to 100 PeV with LHAASO in one year observation. The knee structure will be significantly measured if it is as the assumption of model in [10]

ing the cuts indicated by the dotted lines in Figure 7. The total number of selected showers is about 26,000 above 10 PeV and 200 events in the last bin near 100 PeV. In fact, the difference between the two types of showers is not very significant. The down side is the energy resolution becoming slightly worse due to the mixing of composition. From 18% for pure iron, showers worsen to 20% for the mixed heavy samples. The expectation of the spectrum for the mixed sample has been plotted in Figure 8 in solid circles. The composition model in [10] is assumed.

4 Summary

In summary, the LHAASO experiment will enable an effective identification of CR primary species by measuring two independent key parameters of the induced air showers, muon content and shower maximum position in the energy range from 10 to 100 PeV. The selection of pure iron samples with a purity better than 75% has been achieved using the simulation tools developed for

the LHAASO experiment. With such a pure sample, CR shower energy measurements using the total number of Cherenkov photons in the shower image are more certain and precise, i.e. the energy bias is under control within 5% and the resolution is maintained to be nearly a constant of below 20% over the energies at which the knee of the iron spectrum is expected. In this paper, we have demonstrated the power of the LHAASO experiment in shower composition analysis with a very simple cut. Together with the observation of the knee of the $P+He$ spectrum [2] and the future observation of the pure proton spectrum around 1 PeV in the early stage of the LHAASO experiment [11, 12], one would expect the measurements described in this paper to bring us a clear picture of the phenomena associated with the knees or even more detailed structures of the CR spectra over the whole knee region. It will greatly enhance our knowledge on the mechanism of knees, propagation and the production of the galactic CRs.

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