Frascati Physics Series Vol. 64 (2016)
Frontier Objects in Astrophysics and Particle Physics
May 22-28, 2016

PROSPECTS OF SPECTRUM MEASUREMENTS FOR INDIVIDUAL SPECIES OF COMIC RAY PARTICLES ABOVE 100 TEV USING LHAASO ARRAY

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Abstract

Recently the knee of the spectrum of a mixed cosmic ray proton and Helium nuclei was found below 1 PeV by the hybrid experiment with ARGO-YBJ and a prototype Cherenkov telescope of LHAASO project. A similar measurements about the knees will be carried out with significantly improved performance of identification of primary particles and enormous statistics using the LHAASO instruments. The first 1/4 LHAASO array including 6 Cherenkov telescopes covering a solid angle of ∼0.2 sr, 22,500 m^2 water Cherenkov detector and an array of muon detectors covering 250,000 m^2 using about 10,000 m^2 muon-sensitive area will measure air showers with great details. Here we present a preliminary investigation on the capability of particle identification, in particular for pure proton samples. More sophisticated analysis is under development.

1 Introduction

The knee of the spectrum of a mixed cosmic ray proton and Helium nuclei was found around 0.7 PeV [1] [2] by the hybrid experiment with ARGO-YBJ and a prototype Cherenkov telescope of LHAASO project [3] [4]. The result "gives fundamental inputs to galactic cosmic ray acceleration models", as the paper concluded [1]. ARGO-YBJ fully covered RPC detector measured the air shower cores and nearby particle distributions precisely, thus the telescope was enabled to measure the shower energy with a Gaussian resolution of 25% nearly unbiased over the range from 100 TeV to 3 PeV. Combining the shape of lateral distribution near the cores with the shower Cherenkov image Hillas parameters together, the primary protons and Helium nuclei (H&He) are identified out of the well selected good samples of showers which hit in the RPC array. The purity of the selected sample reached 93% below 0.7 PeV [5]. Even if the contamination of heavier nuclei increases with shower energy from 2.5% at 125 TeV to 13% at 1 PeV, a clear deviation from the single index power law spectrum was observed above 0.7 PeV, indicating the knee of the $H\&He$ spectrum being around 0.7 PeV. Limited by the aperture of the telescope, only 94 events were collected above 0.8 PeV, thus a large uncertainty of the knee energy and the spectral index of the $H\&He$ spectrum above the knee still remained [1]. Moreover, establishing a pure H sample and observing the knee of the proton spectrum are still a dream so far. LHAASO will enable the measurements with greatly improved performance due to the scale of the experiment. LHAASO is an air shower array at high altitude of 4410 m above sea level. The coverage of the array is 1.3 km^2 with 5195 scintillator detectors with a spacing of 15 meters and 1171 water Cherenkov muon detectors with a spacing of 30 meters, a big water pool in the center of the array with 3000 Cherenkov detector cells of $5m \times 5m$ and 12 air Cherenkov/fluorescence telescopes. In 2018, the first 1/4 of the experiment will start operating providing a large amount of data, so that relevant results on cosmic ray physics will be already achievable in only one year of data taking. The 1/4 array will include 6 Cherenkov telescopes covering a solid angle of $\sim$0.2 sr, 22,500 m^2 water Cherenkov detector and an array of muon detectors covering 250,000 m^2 using about 10,000 m^2 muon-sensitive area. The operation of such an instrument for one year will yield a sample of more than 100k well reconstructed air shower events above 0.1 PeV with the cores, arrival directions and energies being measured at the resolution of 3 m,

0.3° and 20%, respectively. The lateral distributions of energy fluxes in the area of 25 m^2 near the shower cores, Hillas parameters of shower Cherenkov images, remaining energies of the showers as they hit into the pond and muon content are measured simultaneously. Combining the shower energy together, those parameters will be useful to identify the composition of the primary particles with high purity. The goal is to establish a pure proton sample of at least 20,000 events in one year, and measure the knee of the proton spectrum using LHAASO. In this paper, we are exploring the way of reaching the specific goal.

2 Detectors, Measurements and Uncertainties

The atmosphere above the LHAASO Water Cherenkov Detector Array (WCDA) watched by the Wide Field-of-View Cherenkov Telescope Array (WFCTA) and the surface detector arrays, WCDA and Muon Detector Array (MDA), form a complete shower detector complex.

WCDA is a water pond with a depth of 4.5 m divided into 900 cells. Each cell has two PhotoMultiplier Tubes (PMT) anchored on the bottom at the center of the cell of 5m$\times$5m. The photocathodes of the PMTs are 1 inch and 8 inch (the ratio of the cathode area is 101:28353), respectively. The larger one is for small signals from 1 photoelectron (PE) to 3000 PEs, and the smaller one catches large signals equivalently from 2800 to 28,000,000 PEs. Secondary electrons and photons falling in the cell will induce cascade processes which produce Cherenkov light in water. The light intensity is proportional to the total energy carried by the air shower electrons and photons in the cell. The larger PMT will time the arrival of the secondary particles with a resolution of 2 ns. The energy flux, which falls rather rapidly with the distance from the cell to the shower core, will be measured by the PMTs with the resolution of 50% about 10 PE on the smaller PMTs and 1% about 100,000 PEs, respectively [6]. Combining the temporal and spatial distribution of the secondary particles, one will reconstruct the shower arrival direction at the resolution of 0.3° and core position at the resolution of 3 m. The total amount of the energy, measured by the total number of equivalent PEs on PMTs, in the cell hit by the core mainly carried by high energy photons and electrons produced in last few generations of the air shower without suffering many Coulomb scattering. Therefore, it is a good measure of the hadrons produced in the last few generations, thus a useful parameter sensitive to the identity of the primary particle, because the number of hadrons in a shower reduces with the elongation of the shower quite sensitively [7].

Each WFCT in the array of 6 telescopes has a light collecting area of 5 m^2 and a camera of 1024 pixels, each of them covering a patch of the sky of 30' in angular diameter, watching a FoV of $14^\circ \times 16^\circ$ [8]. Pixel detector is a SiPM followed by a flash A/D convertor-based (FADC) front end electronics (FEE) [9]. Air showers in the FoV will be imaged by at least 10 registered pixels. Given the accurately measured shower geometry by WCDA, the telescopes will be useful in measurements of total energy and image shape of the shower. Light intensity weighted length (L) and width (W) of the image are sensitive to the identity of the primary particle. The ratio of L/W is an optimized parameter i.e. separation between the distributions of the ratios due to the light and heavy primaries is found rather significant [1].

MDA is an array of underground water Cherenkov detectors. In this paper only 300 MDs partially surrounding WCDA is relevant. The layout of the array is illustrated in Figure 1. Each MD is burred 2.5 m below the surface to screen electrons and photons in air showers. The detector is a 36 m^2 cylinder filled with pure water with a depth of 1.2 m and having a single 8" PMT installed on the top at the central position. Cherenkov photons produced inside the detector by muons will eventually reach to the PMT through a complex path of reflections on the inner surface of the detector. The efficiency of muon detection is better than 95% for every detector [10] .

Using all detector arrays in LHAASO, therefore, one is able to measure a shower with at least 5 relevant parameters in addition to the basic shower geometrical parameters, i.e. shower energy by WFCT, shower image shape by also WFCT, energy flux near the shower core by the 5m×5m cell hit by the shower core in WCDA, remaining shower energy by also WCDA and muon content outside the core region of the shower by MDA. They are rather independent parameters since image shape is an indicator of the depth of shower maximum, energy flux near the core measures the number of hadrons in the latest generations in the cascade process, the remaining energy illustrates the age of the shower as it hits on the ground and the number of muons measures the large transverse momentum hadron production in the whole cascading history. The shower energy is determined by using the total number of photoelectrons in the shower image measured by WFCT, which is in fact dependent of the primary composition [1]. In the hybrid measurement, however, the remaining shower energy measured by WCDA could help the energy deposit in the air measured by WFCTs to improve the energy resolution and reduce the systematic dependence of the primary composition. Following the iteration procedure suggested in ref. [1], one may eventually reconstruct the shower energy after their primary composition is well determined. In the iterating procedure, the entanglements between the parameters can be greatly weakened by grouping showers according to their energies. Thus, the shower composition is able to be also determined with a minimized systematic uncertainty, except for that due to the interaction models.

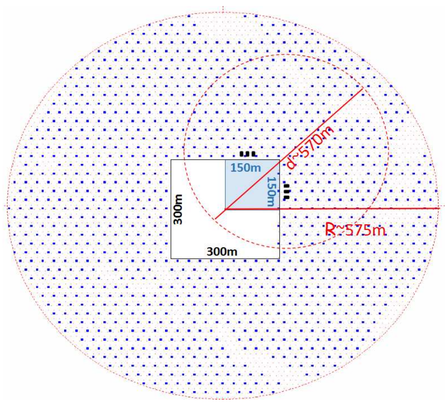

Figure 1: *The layout of the central part LHAASO. The red dotted circle includes the components of the 1/4 LHAASO array considered in this paper: a) the 22,500 m^2 pool of WCDA (indicated by the shaded square), b) $\sim$ 200 MDs (indicated by blue dots), c) 6 telescopes of WFCTA near the pool (indicated by filled black squares).*

The uncertainty due to the interaction models can be partially estimated by means of LHC data. For both region of pseudo rapidity from 8.81 to 8.91 and greater than 10, the models such as EPOS-LHC, SIBYLL 2.1 and QGSJet-II 04 reproduce the distributions of secondary gamma-like and neutron-like particles with energy from 200 GeV to 3 TeV with reasonable accuracy. For instance, the predictions of those models are all deviating from the data taken by LHCf experiment [11], but less than $\pm 50\%$ for gammas and neutrons below 2 TeV.

Above 2 TeV, deviation is still significant. Muon content in air shower has even larger uncertainty in predictions of those models. As an example, if the experiment NA22 data about the π^0 and ρ^0 production were take into account in SIBYLL, the content of muon with energy greater than 1 GeV in a proton shower at 100 EeV would be boosted by a factor of 2 [12] comparing with the current version SIBYLL 2.1. Those uncertainties have to be put in mind as they are used in the composition analysis described below.

3 Identification of Primary Particles

With all those uncertainties in mind, we have studied the shower parameters suitable for cosmic ray composition measurements. We carefully evaluate the parameters for their sensitivity to the composition of the primary particle and possible correlation between them. In the following we will describe the most relevant five parameters and corresponding mass separation capabilities, determined by simulating primary particles of different species and energy, using the QGSJetII hadronic interaction model.

As mentioned, the total number of photoelectrons in the Cherenkov image N^{pe} is a good shower energy estimator, if it is normalized to $R_p = 0$ and $\alpha = 0$ where R_p is the impact parameter of the shower axis to the Cherenkov telescope and α is the space angle between the shower direction and the optical axis of the telescope. The normalized parameters is denoted as $N_0^{pe} = log_{10}N^{pe} + 0.0092(R_p/1m) + 1.05tan\alpha$.

The energy flux near the core as parameter $p_F = log_{10}W_{max} - 1.39log_{10}N_0^{pe}$, where W_{max} is the total number of equivalent photoelectrons recorded by the small PMT in the water Cherenkov detector cell hit by the shower core. The energy dependence is reduced in the definition. The separation of the p_F distributions is 36% in average between proton and iron. The width of the p_F distribution is typically 32% for proton and 14% for iron, respectively.

The WFCTs watches shower longitudinal development from a distance of R_p and take it as the shower image. Because the shower geometry is precisely measured by WCDA, the distribution of number of photoelectrons in the image along the shower axis describes the shower profile at certain precision. The centroid of the image indicates the shower maximum position in sky while the direction of the shower points the start of the shower. The angular distance $\Delta\theta$ between the shower arrival direction and the centroid could be used to measure the atmospheric depth for shower maximum. However, the image is stretched longer for farther showers due to pure geometric effect. Defining the parameter $p_X = \Delta\theta - 0.0097R_p - 0.47log_{10}N_0^{pe}$, one can reduce the geometrical effect, and the shower elongating effect. The separation of the p_X distributions is about 23% in average between proton and iron. The width of the p_X distribution is typically 28% for proton and 21% for iron, respectively.

The ratio of length L and width W of the shower Cherenkov image taken by WFCTs, as mentioned above, can be used to define a dimensionless parameter, $p_C = L/W - 0.0139R_p + 0.267log_{10}N_0^{pe}$. Here, the pure geometrical elongation effect of the image due to the spatial distance of the shower axis from the telescope and the energy dependence are reduced in the definition of p_C. The separation of the p_C distributions is 42% in average between proton and iron. The width of the p_C distribution is typically 20% for proton and 24% for iron, respectively.

The μ-content is measured using the MDs in the array surrounding WCDA. For showers well contained in WCDA, the registered MDs distribute at least 30 m away from the shower core and spread out a large area in MDA. Simulation shows that the average number of muons recorded by all MDs is about 18 for showers between 100 TeV and 130 TeV. Due to the rather rapidly falling lateral distribution of muons in a shower and the uneven distribution of the detectors respect to WCDA, the number of muons recorded by MDs varies very much depending on the shower core position in WCDA. A fitting procedure is developed to obtain the total muon content N_μ in the shower. Below 10 PeV, the energy dependence of the muon content is nearly universal for all species. The separation of the distributions of parameter describing the muon content, defined as $p_\mu = log_{10}N_\mu - 0.982log_{10}N_0^{pe}$ to reduce the shower size dependence, is about 3.7% between proton and iron, with typical widths of 3.4% for proton and 2.8% for iron, respectively.

Figure 2 shows the one-to-one correlation between the described parameters for different species of well reconstructed events generated assuming a primary composition of equal-weighted 5 mass groups (H, He, CNO, $AlMgSi$, Fe) and a spectral index being -2.7 [1)] below the knee and -3.1 above, respectively. The knee for each spectrum is assumed to be at $700Z$ TeV where Z is the average charge of the mass group. Further analysis with different assumptions on mass composition and spectral indices will estimate the corresponding uncertainty. Selections for samples of either pure protons or pure iron are rather straightforward using the two-parameter analysis by setting cuts on the correlation maps. Using an assumption proposed by Horandel [13] for heavier compositions as the background of the pure proton sample, the purity of 90% for the proton sample can be reached with sufficiently high selecting efficiency. For a mixed sample of proton plus Helium nuclei, $H\&He$, it is possible to reach an even higher purity such as 95%. An example of using the particle density near the shower core instead of the energy flux p_F and the parameter p_C of the Cherenkov image, has been the analysis of the data produced by the combined experiment with one LHAASO prototype telescope and the ARGO-YBJ RPC carpet detector. With this technique, the important discovery of the knee at energy below 1 PeV in the $H\&He$ spectrum has been made (ref. [1]). An enhancement of a factor of ~ 18 in statistics with the 1/4 LHAASO array is foreseen in one year of measurement. The expected number of events per year for proton and $H\&He$ samples with the corresponding purities are shown in Figure 3.

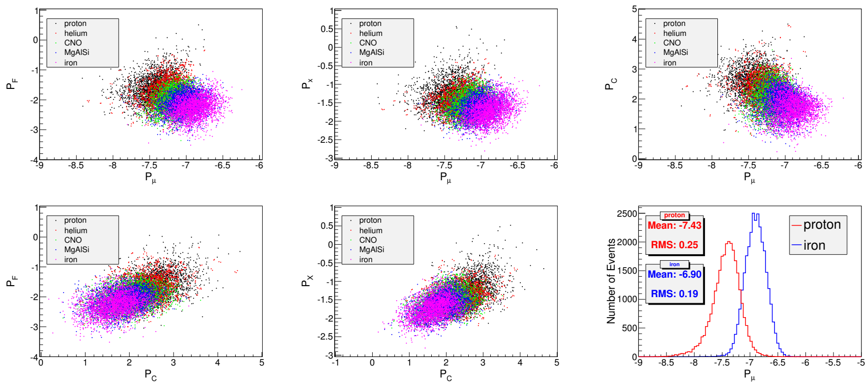

Figure 2: *One-to-one correlation between the parameters p_F, p_X, p_C and p_μ for different species of well reconstructed events (see the text for the assumption on composition and spectral index). The color indicates the particle type (black for proton, red for helium, green for CNO, blue for MgAlSi and pink for Fe). The last figure shows the p_μ distributions for proton and iron showers, as an example of how the two species can be separated using this parameter.*

To separate other species, such as Helium or CNO, out from all reconstructed events, more sophisticated analysis techniques in the multi-parameter measurements have been under development, for instance the Artificial Neuron Network, Boosted Decision Tree or other methods will be used in the analysis.

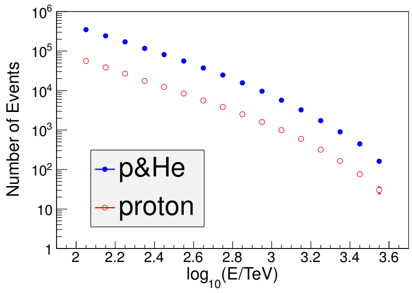

Figure 3: *The integrated distribution of number of events per year for 1/4 LHAASO array. The open dots represent pure proton samples with a purity of 90% and the filled dots represent $H\&He$ samples with a purity of 95%, respectively. The duty cycle is assumed to be 15%.*

4 Summary

Separation between proton or $H\&He$ showers from well measured air shower samples by 1/4 LHAASO array is briefly discussed in this paper. With multiple parameters, i.e. shower energy,p_F, p_X, p_C and N_μ, being measured, one can select pure proton or $H\&He$ samples with high purity by applying simple cuts on the one-to-one correlation maps. More than 2500 proton events above the knee of 700 TeV would be collected in one year operation with an assumption of 15% duty cycle. The heavier nuclei can be also separated out by more sophisticated analyses which are under development. A pure proton samples with well determined shower energy are much more useful than simply measuring the spectrum. For instance, they will help to understand many details of interaction models, particularly for the muon production. It is well known that there is still big uncertainty in the models. One of the good feature of such a sample is that the energy of protons is determined independent of the muon content of showers.

5 Acknowledgements

This work is supported in China by the Chinese Academy of Sciences (CAS) (0529110S13), the Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS. Projects No. 11475190 and 11505190 of NSFC also provide support to this study.

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