PROCEEDINGS OF SCIENCE

The anisotropy of cosmic ray light and heavy components observed by LHAASO-KM2A

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The anisotropy in different mass components of cosmic rays can provide stringent constraints on theoretical models regarding the origin of anisotropy, such as the distribution of sources, the propagation of cosmic rays, and the local magnetic field environment. This is particularly significant in the high-energy range, from hundreds of TeV to PeV, where the anisotropy exhibits considerable variation. However, to date, the cosmic-ray anisotropy of different mass compositions in this high energy range are not reported. The muon measurements from the LHAASO-KM2A offer an opportunity to identify the components of cosmic rays. In this study, we utilize three years of data from KM2A to measure the anisotropies of different mass composition ratios across tens of TeV to PeV range. We obtained high-purity samples of light and heavy component cosmic rays, and our findings indicate that the anisotropies show variations for lighter components at lower energies.

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1. Introduction

The arrival direction of cosmic rays shows a weak anisotropy. The morphology and intensity of anisotropy change significantly with energy. There are still many puzzles for the anisotropy origins. Nonetheless, it is generally believed that the cosmic-ray anisotropy may be related to the distribution of sources, the propagation of cosmic rays, and the local magnetic field environment etc. Thus the weak anisotropies serve as important probes for theories of both the transport and accelerations of cosmic rays [1–3]. The measurement of anisotropy in divided mass components will provide strict constraints on these theoretical models of anisotropy origin. Especially, in the high-energy range, from hundreds of TeV to PeV, where the anisotropy varies significantly. The difficulty in identifying the mass components of high-energy cosmic rays has limited previous EAS-based observations to measuring only the mixed components. Additionally, the anisotropy of cosmic rays with different mass compositions remains poorly understood.

The Square KiloMeter Array (KM2A), the largest sub-array of the Large High Altitude Air Shower Observatory (LHAASO) with an effective area of $\sim 1km^2$, consists of two types of detectors: an electromagnetic detector (ED) array on the surface and a muon detector (MD) array shielded by a 2.5-meter layer of soil. KM2A covers the energy range from 10 TeV to 100 PeV, enabling anisotropy measurements from tens of TeV to multi-PeV. The muon content and electromagnetic particles are sensitive to some extent to the energy and composition of primary cosmic rays, enhancing particle identification capabilities. Thus, KM2A can observe the anisotropy more precise at high energies, and it can also distinguish primary mass composition of cosmic rays to achieve the light and heavy components of cosmic-ray anisotropy. The measurement of different mass composition of cosmic-ray anisotropy will provide constraints on the origin of anisotropy and the propagation of cosmic rays.

2. Simulation and Data selection

The Monte Carlo simulation was conducted to reconstruct the primary energy of cosmic rays. The CORSIKA7.74 code [4] was employed to simulate the process of EAS. For high-energy hadronic interaction, the QGSJETII-04 [5] model was utilized, while for low-energy interations, the FLUKA code [6] was employed. The responses of KM2A array were simulated using the G4KM2A code [7], which is based on the GEANT-4 [8]. Approximately 5.56×10^8 events were sampled with zenith angles ranging from 0° to 40° and energies spanning 1 TeV to 10 PeV. The composition and energy spectrum of the simulated events adhere to those presented in [9].

The experimental data from KM2A, collected between August 1, 2021, and July 31, 2024, were used for analysis. After quality checks [10], the data underwent further screening to remove events with poor reconstruction accuracy. The following criteria were applied: (1) Events with zenith angles less than 40 degrees were selected to avoid large zenith angle events with poor reconstruction accuracy. (2) Events with electromagnetic particle counts and muon counts no less than 20 and 10, respectively, were retained to exclude events near the threshold and gamma-ray events. (3) Events with core positions within an annular region of radius 280–500 meters from the array center were selected to exclude events with core positions at the array edges, which have lower reconstruction accuracy. (4) The reconstructed energy, expressed as $log(E_{rec}/GeV)$, should be above 4.5. The primary energy of the selected events is reconstructed using a specific method [11].

3. Component identification

In the empirical model of cosmic ray showers[12, 13], the relationship between the number of electromagnetic particles (N_e) and the primary cosmic ray energy (E_0) and composition (A, mass number) is given by:

$$N_e \propto A^{1-\alpha} \left(\frac{E_0}{\xi_{c\pi}} \right)^{\alpha}, \quad \alpha \approx 1.046.$$

Similarly, the relationship between the number of muons (N_μ) and the primary energy (E_0) and composition (A, mass number) is:

$$N_\mu \propto A^{1-\beta} \left(\frac{E_0}{\xi_{c\pi}} \right)^{\beta}, \quad \beta \approx 0.85.$$

The muon number is the most sensitive parameter to the primary cosmic ray composition (A): heavier compositions (larger A) result in higher muon content (N_μ). Therefore, the muon content can be used for composition discrimination.

As KM2A simultaneously measures the number of electromagnetic particles and muons. Using these two parameters, we constructed a composition-sensitive parameter $C_{e,\mu} = \frac{N_\mu}{N_e^{0.85}}$. Here, N_e represents the number of electromagnetic particles within a 200-meter radius from the core position, while N_μ denotes the number of muons within the annular region between 40 and 200 meters from the core position. The left plot of Figure 1 shows the distribution of the composition-sensitive parameter. The data are divided into two categories: the light component (proton and helium) and the other components, which are classified as the heavy component. The light component exhibits lower values of the parameter, while the heavy components exhibit higher values. A specific threshold of $C_{e,\mu}$ can be used to distinguish between light and heavy components. To illustrate the selection process, we focus on the light components. In order to obtain high-purity samples of light components, we systematically scanned the purity, selection efficiency, and retention rate for various threshold values. The results are presented in the right plot of Figure 1. A 90% purity light component sample is selected with $C_{e,\mu} < C_{90}$, where C_{90} is the threshold derived from simulations for 90% purity.

4. Primary Result

The KM2A data were divided into seven energy intervals based on the reconstructed energy. For each interval, the threshold C_{90} for the light component was determined through a scanning process (section 3). Table 1 lists the C_{90} values, median energy, and event counts for the selected light component (with 90% purity), heavy component, and all-particle samples. It should be noted that the heavy component samples were not selected in the same manner as the light component. Instead, the heavy component was defined as the residual data after selecting the light component, which results in unstable purity across different energy ranges. The selected data samples for the light, heavy, and all components were analyzed using the equi-zenith angle method. Their right

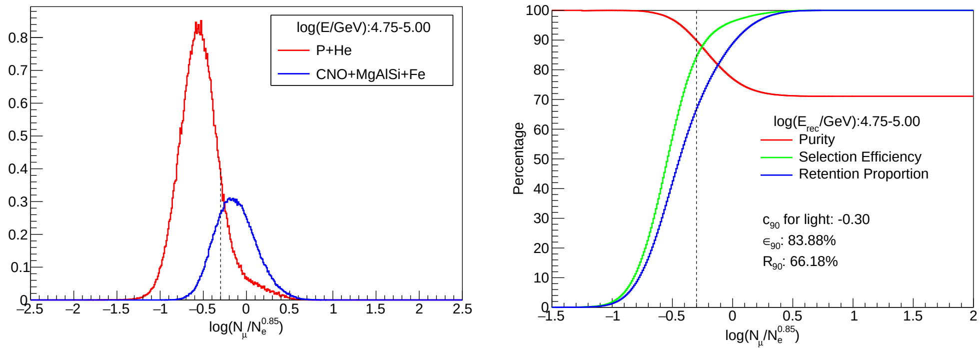

Figure 1: The composition dividing according to $C_{e,\mu}$

ascension projections were fitted with a second harmonic function, and the first-order amplitude and phase of anisotropy are shown in Figure 2 for comparison. Since the light component is dominant, the energy evolution of the amplitudes for all particles closely follows that of the high-purity light component data. In contrast, the heavy component exhibits smoother and more stable energy evolution, with significantly larger anisotropy intensity. The anisotropy of the light component sample shows more pronounced variations with increasing energy, particularly at lower energy levels. Although the results for the heavy component are preliminary, the three component samples confirm that anisotropies are strongly linked to composition. The differences in the energy evolution of anisotropy among the component data samples provide observational evidence for theoretical studies of cosmic ray acceleration and propagation.

E_{rec}/GeV	4.50-4.75	4.75-5.00	5.00-5.25	5.25-5.50	5.50-5.75	5.75-6.00	$\geq$ 6.00
C_{90}	-0.29	-0.30	-0.36	-0.41	-0.45	-0.49	-0.55
$N_{light}(\times 10^8)$	67.85	47.64	19.40	7.63	2.91	1.08	0.58
$N_{heavy}(\times 10^8)$	55.25	27.57	11.65	4.50	1.60	0.58	0.37
$N_{all}(\times 10^8)$	123.03	75.17	31.03	12.12	4.51	1.66	0.95

Table 1: Data messages of light and heavy data samples

5. Discussion

We utilize three years of data from LHAASO-KM2A to measure the large-scale anisotropy of cosmic rays from multi-TeV to PeV. Benefiting from the multi-parameter measurement capability of KM2A for cosmic ray extensive air showers (EAS), we developed a composition identification method based on the muon content and electromagnetic particles. We obtained three data samples: all particles, a light component with 90% purity, and a heavy component, which consists of the residual events after selecting the light component. The anisotropy of these three samples was observed, and it varies with increasing energy. The amplitude and phase evolution exhibit a composition-dependent variation with energy, with lighter compositions showing variations starting at lower energies.

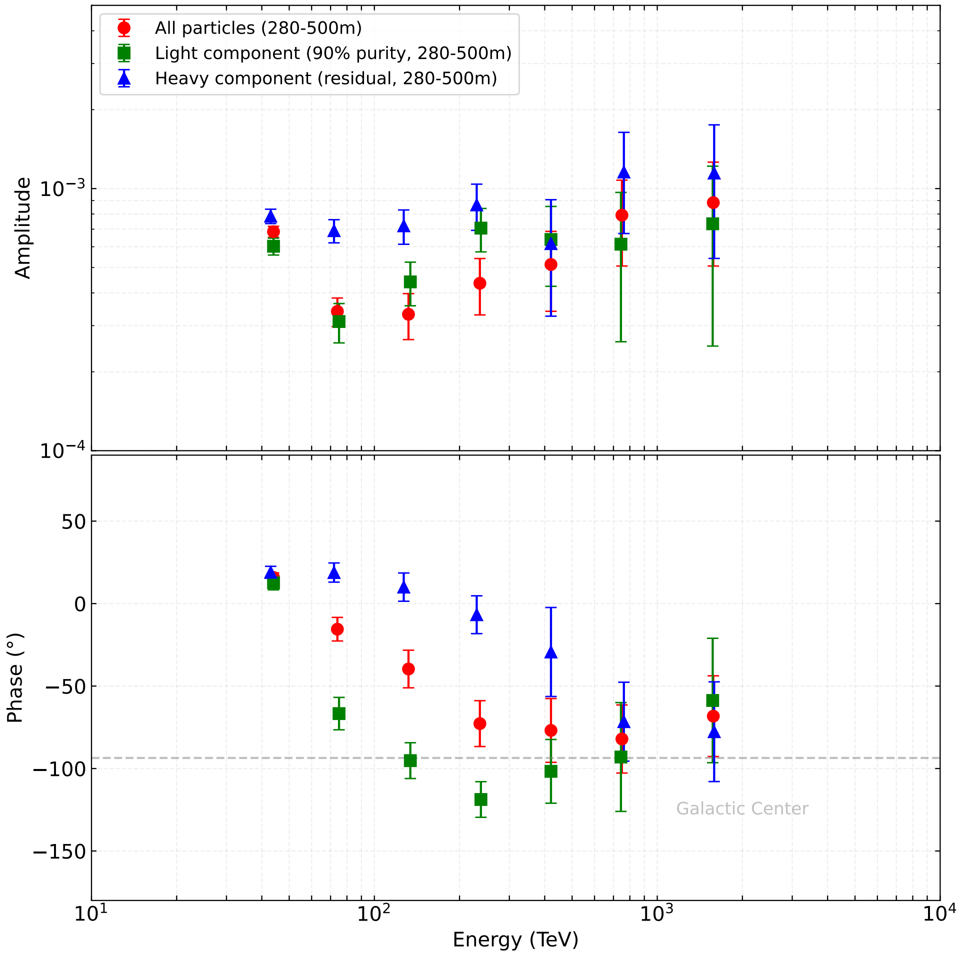

Figure 2: The anisotropy evolution of all particles, the light component (with 90% purity), and the heavy component of cosmic rays with increasing energy. The heavy component represents the residual data sample after selecting the light component.

In future work, we will select a stable ratio of heavy components, such as the Fe composition, to study the anisotropy of heavier cosmic rays. Additionally, while this analysis is based on the composition model of [9], other models and simulations need to be analyzed to estimate the systematic errors arising from the models. Our future work will focus on this and aim to interpret the results using theoretical models.

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