Chemical Composition of Ultra-high Energy Cosmic Rays Observed by AGASA

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Abstract

We have observed ultra-high energy cosmic rays above the Greisen-Zatsepin-Kuz'min cut-off energy by Akeno Giant Air Shower Array. Their chemical composition is a key discriminator of origin models. In the present work, we estimate the average composition by an analysis of muons in air showers with AIRES+QGSJET simulation. The data matches the prediction for light hadron primaries and no indication has been found for a gamma-ray dominance.

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1. Introduction

We have observed a significant number of ultra-high energy cosmic rays (UHECRs) by Akeno Giant Air Shower Array (AGASA) [12] whose energies exceed the predicted Greisen-Zatsepin-Kuz'min cut-off ($\sim 5 \times 10^{19}$ eV) [3]. With conventional acceleration process, possible candidates are only a few types of astrophysical objects and so far no UHECR origin has been confirmed. 'Top-down' scenarios are another approach to explain UHECRs as decay or interaction products of exotic particles with super-high energies. Observed UHECRs are predicted to be gamma-rays and nucleons (see [8] for review).

Concerning the puzzle of UHECR origin, it is important to study the chemical composition of UHECRs taking into account a possibility of gamma-ray primaries. In the present work, we use muon density at 1000 m from the shower core [$\rho_\mu(1000)$] as a primary mass estimator. We perform a detailed analysis of muons in showers above 10^{19} eV. We estimate the UHECR chemical composition on a two-component assumption of proton plus iron in comparison with simulations. We also present an upper limit on the gamma-ray fraction in UHECRs.

2. Experiment and analysis

AGASA (see [2] for details) is located at Akeno, Japan (900 m asl). The atmospheric depth is 920 g cm^{-2}. Over an $\sim$100 km^2 area, we deploy 111 stations where a 2.2 m^2 surface detector is installed. Muon detectors are also set in 27 stations in the southern region and are triggered by the nearby surface detector. The threshold energy is 0.5 GeV for vertically incident muons. Each detector has a 2.8–10 m^2 area and is capable of measuring muon densities up to $\sim$ 10 m^{-2}.

In the present work, events between 1996 and 2002 are selected by the following criteria: (1) energy $E_0 \geq 10^{19}$ eV; (2) zenith angle $\leq 36°$; (3) six or more hit surface detectors; (4) good fitting on shower geometry; (5) core location greater than 600 m inside boundary of surface detector deployed area and (6) two or more muon detectors between 800 and 1600 m of shower core. The number of selected events is 129, 19, and 5 above $10^{19}, 10^{19.5}$ and 10^{20} eV, respectively.

For each event, $\rho_\mu(1000)$ is determined by density data within 800–1600 m distances fitted with the empirical lateral distribution function [4]. This function is found to be in agreement with experimental data up to 10^{20} eV [10]. The accuracy of $\rho_\mu(1000)$ is evaluated to be 40% by analyzing artificial showers.

In order to interpret the data, we perform the air shower simulation (see also [6]) with AIRES code [9] plus QGSJET model [5]. Proton, iron and gamma-ray primaries are tested. For gamma-ray showers, we take account of Landau-Pomeranchuk-Migdal effect [6] and electromagnetic interaction in geomagnetic field (GF). This process is implemented by sub-simulation code [13].

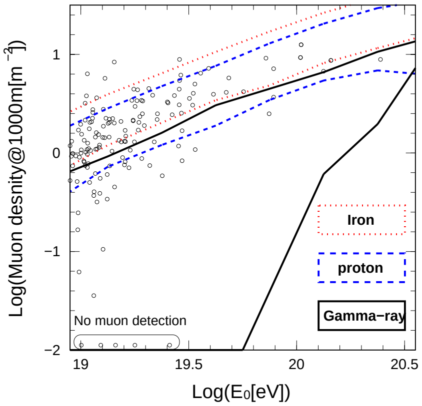

Fig. 1. $\rho_\mu(1000)$ vs. E_0 relations for observed events (circles). Expected ±1 σ bounds for the distribution are indicated for proton, iron and gamma-ray primaries by different curves as in the legend.

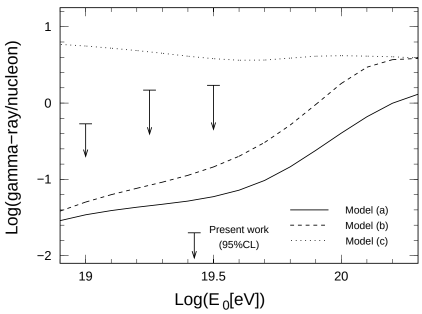

Fig. 2. Gamma-ray to nucleon ratio as function of threshold E_0. Arrows denotes the present upper limits at a 95% CL. The different curves as in the legend indicates the predictions from origin models: (a) decay from TDs; (b) Z-burst model; (c) decay from SH particles). See description in the text.

3. Results and discussion

Fig. 1 shows $\rho_\mu(1000)$ vs. E_0 relations for observed events (circles). Expected ±1 σ bounds for the distribution are indicated for proton (dashed curves), iron (dotted curves) and gamma-ray primaries (solid curves).

The $\rho_\mu(1000)$ distribution fits the proton expectation best among the simulated primaries. Assuming a composition of proton+iron, we estimate the fraction of iron by fitting the distributions from data and simulation for three different threshold energy. As far as we use the present simulation code and hadronic interaction model, the average fraction of iron is $14^{+16}_{-14}\%$ and $30^{+7}_{-6}\%$ above 10^{19} and $10^{19.25}$ eV, and is less than 66% at a 1 σ bound above $10^{19.5}$ eV. Around 10^{19} eV, the present result indicates a relatively light composition and is consistent with ones from other experiments (Fly's Eye, Yakutsk and Haverah Park) that are based on measurement of longitudinal development (see $\langle X_{\max}\rangle$ vs. E_0 plot summarized in [7]).

To estimate the fraction of gamma-ray showers in observed events, we similarly assume a composition of proton+gamma-ray. Upper limits on the gamma-ray fraction are given at a 95% confidence level (CL) to be 34%, 59% and 63% above 10^{19}, $10^{19.25}$ and $10^{19.5}$ eV, respectively. It should be noted that an estimated gamma-ray flux depends on hadronic interaction models assumed, i.e. models predicting the heavier mass composition give the lower fraction of gamma-rays.

In Fig. 2, we summarize the result as gamma-ray to nucleon ratio along with predictions from the models: (a) decay from topological defects (TDs; solid curve) [11] and (b) Z-burst model (dashed curve) [11]; and (c) decay from superheavy (SH) particles (dotted curve) [1]. See also [10] and references therein.

In Model (c), we show the case of all UHECRs above 10^{19} eV being decayed from SH particles. The predicted ratio is rather high to the present limits. Also in Model (b), gamma-rays are expected to be dominant above 10^{20} eV. As seen in Fig. 1, no clear dominance is observed. If all events are gamma-ray showers above 10^{20} eV, an anisotropy may be expected with respect to the GF since the magnitude of electromagnetic interaction with field depends on gamma-ray energy and GF strength. In Akeno, an excess is expected for arriving showers from northern sky region. In our data, no indication has been found to imply a possible dominance of gamma-rays. This signature also provides an observational constraint on origin models up to the highest energies.

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4. References

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