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# Properties of EHE gamma-ray initiated showers and their search by AGASA

**K. Shinozaki**[4], **M. Chikawa**[2], **M. Fukushima**[1], **N. Hayashida**[1], **K. Honda**[3], **N. Inoue**[4], **K. Kadota**[5], **F. Kakimoto**[6], **K. Kamata**[7], **S. Kawaguchi**[8], **S. Kawakami**[9], **Y. Kawasaki**[10], **N. Kawasumi**[11], **E. Kusano**[12], **A.M. Mahrous**[4], **K. Mase**[1], **S. Mizobuchi**[13], **Y. Morizane**[2], **M. Nagano**[14], **H. Ohoka**[1], **S. Osone**[1], **N. Sakaki**[10], **M. Sasaki**[1], **M. Sasano**[15], **M. Takeda**[1], **M. Teshima**[1], **R. Torii**[1], **I. Tsushima**[11], **Y. Uchihori**[16], **K. Yasui**[2], **T. Yamamoto**[1], **S. Yoshida**[1], **and H. Yoshii**[13]

[1]Institute for Cosmic Ray Research, University of Tokyo, Chiba 277-8582, Japan
[2]Research Institute for Science and Technology, Kinki University, Osaka 577-8502, Japan
[3]Faculty of Engineering, Yamanashi University, Kofu 400-8511, Japan
[4]Department of Physics, Saitama University, Saitama 338-8570, Japan
[5]Faculty of Engineering, Musashi Institute of Technology, Tokyo 158-8557, Japan
[6]Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan
[7]Nishina Memorial Foundation, Komagome, Tokyo 113-0021, Japan
[8]Faculty of Science and Technology, Hirosaki University, Hirosaki 036-8561, Japan
[9]Department of Physics, Osaka City University, Osaka 558-8585, Japan
[10]RIKEN (The Institute of Physical and Chemical Research), Saitama 351-0198, Japan
[11]Faculty of Education, Yamanashi University, Kofu 400-8510, Japan
[12]KEK, High Energy Accelerator Research Organization, Institute of Particle and Nuclear Studies, Tsukuba 305-0801, Japan
[13]Department of Physics, Ehime University, Matsuyama 790-8577, Japan
[14]Department of Space Communication Engineering, Fukui University of Technology, Fukui 910-8505, Japan
[15]Communications Research Laboratory, Ministry of Posts and Telecommunications, Tokyo 184-8795, Japan
[16]National Institute of Radiological Sciences, Chiba 263-8555, Japan

**Abstract.**
A fraction of gamma-rays in extremely high energy cosmic rays (EHECRs) is a key parameter to discriminate models of the origin of cosmic rays beyond the predicted Greisen-Zatsepin-Ku'zmin(GZK) cut-off. In this paper, we discuss observable properties of EHE gamma-ray initiated showers by Monte Carlo (MC) studies with AIRES code and QGSJET interaction model and a search for EHE gamma-ray initiated showers with muon data taken by the Akeno Giant Air Shower Array (AGASA). The result of the muon component analysis is explained by a fraction of gamma-ray initiated showers with an upper limit of 32% at 90% confidence level (CL) above $10^{19}$eV under an assumption of two component primaries of protons and gamma-rays.

## 1 Introduction

The cosmic rays with energies beyond the predicted GZK cut-off (Greisen (1966); Zatsepin and Ku'zmin (1966)) have been gradually accumulated. AGASA has observed some ten events above $10^{20}$eV in the last 11 years (Sakaki, *et al.* (2001)). So far, many models on their origin have been discussed in literatures. Besides traditional 'Bottom-Up' accelerating mechanisms, some 'Top-Down' scenarios have been proposed. The presence of EHE gamma-rays is consequently predicted as decay products of supermassive particles (*Eg.*, Berezinski, *et al.* (1998)) or topological defects (*Eg.*, Berezinski, *et al.* (1997)), or cascade particles initiated by super high energy neutrinos (*Eg.*, Yoshida, Sigl and Lee (1998)).

In order to search for gamma-ray showers by surface-arrays, a fraction of muons in air shower particles may be a possible observable to distinguish from hadronic showers. Due to an inter-detector spacing of ∼1km in AGASA, muon densities at 1000m is used as a mass estimator. At energies of interest, MC studies show that showers of gamma-ray primaries produce a relatively small number of muons, while hadronic primaries leave abundant muons. This means that gamma-ray initiated showers have a muon-poor property. In addition, there are also characteristic effects affecting the electromagnetic component in gamma-ray initiated showers.

In this paper, we will discuss observable properties of gamma-ray initiated showers based on MC studies. The result of a search for EHE gamma-rays and a fraction of gamma-rays in cosmic rays above $10^{19}$eV will be presented by detailed analysis of AGASA muon data.

## 2 Experiment

### 2.1 Apparatus

AGASA is located at Lat. 35°47′N, Long. 138°30′E and 900m asl. 111 stations with a 2.2m$^2$ charged particle detec-

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*Correspondence to:* K. Shinozaki
(kenjikry@crsgm1.crinoue.phy.saitama-u.ac.jp)

tor cover an area of $\sim$100km$^2$. The triggering requirement is a five-fold coincidence among neighboring detectors in a gate width of 25.6$\mu$sec. The triggering bias is free above $10^{18.8}$eV. Muon detectors with various areas of 2.8–10m$^2$ each are in operation at 27 stations in the southern region which are triggered by the charged particle detector at each station. Each muon detector consists of 14–20 proportional counters aligned under shielding materials of 1m-concrete or 30cm-lead. The threshold energy is about 0.5GeV for vertically incident showers. The muon density in this work is determined by the so-called 'on-off' method. Details are referred to Chiba, *et al.* (1992) and Ohoka, *et al.* (1997).

### 2.2 Analysis

In this work, events over $10^{18.8}$eV are selected by following criteria: 1) Period: December 13, 1995 through December 31, 2000, after unification of AGASA branches; 2) zenith angle $\leq 33.6°$, $(\sec\theta \leq 1.2)$; 3) Good fitting of shower geometry; 4) Two or more muon detectors triggered between 800m and 1600m from the core. Criterion 4) is required for the determination of $\rho_\mu(1000)$, the muon density at 1000m from the core, as a mass estimating parameter. $\rho_\mu(1000)$ is obtained by fitting muon densities at that distance range to the empirical lateral distribution function (Hayashida, *et al.* (1995)). The accuracy of $\rho_\mu(1000)$ determination is about 50% on average. The numbers of selected events are 195 and 102 above $10^{18.8}$eV and $10^{19}$eV, respectively.

In this experiment, we use $S(600)$, the charged particle density at 600m[1/m$^2$] measured by 5cm-scintillators as an energy estimator (Yoshida, *et al.* (1994)). For hadronic primaries, the uncertainty of the energy estimation is $\sim \pm 30\%$ above $10^{19}$eV regardless of the primary species or the interaction model used (Takeda, *et al.* (1998)). The uncertainty for gamma-ray showers will be discussed later.

## 3 Simulation

We carried out simulation studies using AIRES code (Scuitto (1999)) with QGSJET interaction model (Kalmykov, Ostpcheko and Pavlov (1997)). The zenith angle is fixed to 24.6°, $(\sec\theta = 1.1)$. In each combination of primary particles (proton, iron and gamma-ray) and energies ($\log E_0$=18.0, 18.1, $\ldots$,21.0 and 16.0, 16.1, $\ldots, 21.0$ for gamma-ray primary), 500 showers are simulated and recorded in the library.

EHE gamma-rays above a few times $10^{19}$eV may interact with the geomagnetic field to initiate cascades above the atmosphere (McBreen and Lambert (1981)). This effect is examined with the MC code programmed by H.P. Vankov (private communication) which simulates cascades in the geomagnetic field down to the top of the atmosphere. The output is used as an input of AIRES to simulate cascades in the atmosphere.

In order to include the detector fluctuation of measurements, we generated a large number of artificial events using simulated showers in the library. Shower geometries are sampled from the real data not only to test errors of $\rho_\mu(1000)$ determination and but also to take into account the arrival direction dependence of geomagnetic effects for gamma-ray primaries. The input primary spectrum for each tested primary particle is adjusted to reproduce the observed AGASA cosmic ray spectrum (Hayashida, *et al.* (2000)).

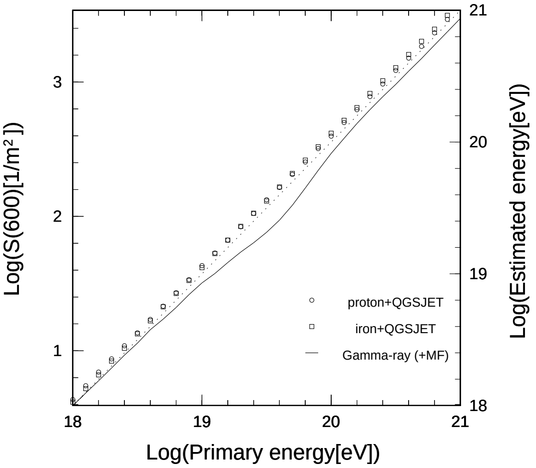

**Fig. 1.** Average $S(600)$ as function of primary energy for $\theta = 24.6°$. The corresponding estimated energy is shown on the right axis. Open circles and squares indicate proton and iron primaries. The solid line shows the gamma-ray. The dotted line shows the conventional energy estimation used in the AGASA Experiment.

## 4 Results

### 4.1 Primary energy estimation

Figure 1 shows average $S(600)$ vs. $E_0$ relation for proton (open circles), iron (open squares) and gamma-ray (solid curve) primaries for $\theta = 24.6°$. The relation used in AGASA experiment is given by a dotted line and the estimated energy scale is shown on the right axis. The uniform azimuthal distribution is assumed for gamma-ray initiated showers.

For gamma-ray primaries, one needs to note another effect working on shower development; The Landau-Pomeranchuk-Migdal (LPM) effect (Landau and Pomeranchuk (1953); Migdal (1956)). Due to the LPM effect, showers of EHE gamma-ray primaries 'slowly' develop and they give smaller $S(600)$ than that of hadronic primaries by 20–30% at energies around $10^{19}$eV. This leads to an underestimation of the primary energy of gamma-rays by $S(600)$. This attributes to a suppression of the shower development due to the LPM effect. At much higher energies, gamma-ray primaries mostly interact with the geomagnetic field off the atmosphere and initiate cascading in the magnetic field where no LPM effect or ionization loss works. At the top of the atmosphere, the primary energy is distributed over a bunch of secondary photons and a few electron-positron pairs. The resultant air shower left after this process develops 'faster'

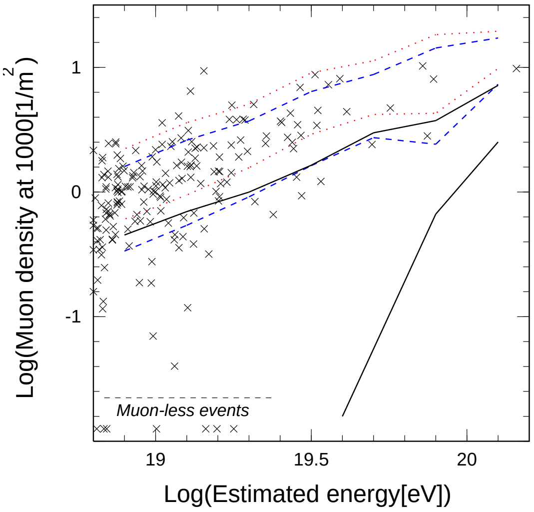

**Fig. 2.** $\rho_\mu(1000)$ vs. $E_0$ relation. Crosses represent individual AGASA events. Muon-less, $\rho_\mu(1000) = 0$ events, are shown in the oval. Dashed, dotted and solid curves indicate upper and lower bounds of $1\sigma$ deviation of $\rho_\mu(1000)$ for proton, iron and gamma-ray primaries, respectively.

as a superposition of lower energy subshowers. This transition appears in non-linear $S(600)$ vs. $E_0$ relation around $5 \times 10^{19}$eV because of a competition between LPM and geomagnetic effects on shower development.

### 4.2 $\rho_\mu(1000)$ vs. $E_0$ relation

Table 1 summarizes the average $\rho_\mu(1000)$ of showers initiated by proton, iron and gamma-ray with estimated energies of $10^{19}$eV, $10^{19.5}$eV and $10^{20}$eV. In the case of gamma-ray primaries, the muon component in the air shower is due to decay products of photonuclear interactions and the average $\rho_\mu(1000)$ is about 20% of that of proton primaries around $10^{19}$eV.

In Figure 2, $\rho_\mu(1000)$ vs. $E_0$ relation is shown. Crosses represent individual events from the experiment. Seven events of $\rho_\mu(1000) = 0$, (called 'muon-less' events, hereafter), are indicated at the bottom of the figure. Dashed, dotted and solid curves indicate upper and lower bounds of $1\sigma$ deviation of $\rho_\mu(1000)$ for proton, iron and gamma-ray primaries. The general features of the muon component can be explained by hadronic primaries, however, air showers with a small muon content may be a candidate of EHE gamma-ray initiated showers. Above $10^{19}$eV, probabilities of observing as muon-less showers are 0.4%, 0.1% and 13% for pure primaries of proton, iron and gamma-ray, respectively. It is noteworthy that four muon-less events above $10^{19}$eV were observed against the expected 0.45 events from MC if primaries are mostly protons. The corresponding Poisson chance probability is less than 0.2%. Thus, we can consider these muon-less events as possible candidates for EHE gamma-ray showers.

**Table 1.** $\rho_\mu(1000)$[1/m$^2$] at estimated energies of $10^{19}$eV, $10^{19.5}$eV and $10^{20}$eV for proton, iron and gamma-ray primaries using the AIRES+QGSJET simulation.

| Estimated $E_0$[eV] | Proton | Iron | Gamma-ray |
|---|---|---|---|
| $10^{19.0}$ | 1.5 | 2.2 | 0.3 |
| $10^{19.5}$ | 4.6 | 6.5 | 1.0 |
| $10^{20.0}$ | 11.2 | 14.0 | 4.4 |

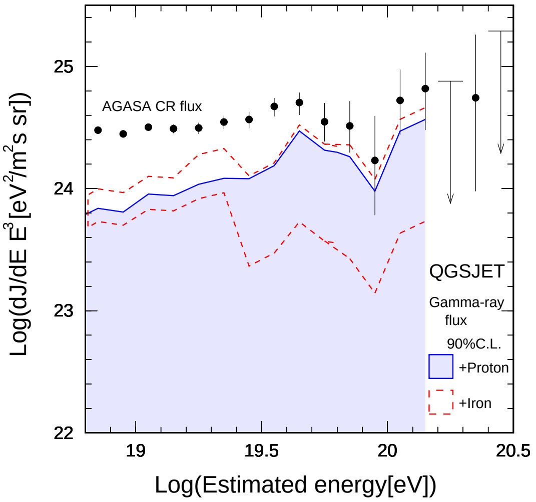

**Fig. 3.** Deduced gamma-ray flux as function of estimated energy. Regions shaded and enclosed by dashed lines indicate upper and lower bounds at a confidence level of 90% for primary combinations of proton+gamma-ray and iron+gamma-ray. Closed circles represent the total cosmic ray flux observed by AGASA (Hayashida, *et al.* (2000)).

### 4.3 Deduction of EHE gamma-ray flux

Figure 3 shows the deduced gamma-ray flux as a function of '*estimated*' energy. Regions shaded and enclosed by thin dashed lines correspond to the permissible fluxes at 90% CL for assumed two-component primaries of proton+gamma-ray and iron+gamma-ray, respectively. Closed circles indicate the total flux of cosmic rays observed by AGASA(Hayashida, *et al.* (2000)). The flux is a convolution of the AGASA cosmic ray spectrum with the most probable proportion of two components obtained by minimizing $\chi^2$ value for $\rho_\mu(1000)$ distribution in each energy bin of $\Delta \log E_0 = 0.2$. Taking the ambiguities in assumed interaction models into consideration, only an upper limit is given for proton+gamma-ray combination.

As described above, energies of gamma-ray primaries estimated by $S(600)$ is systematically lower than that of hadronic primaries. Therefore the EHE gamma-ray flux reflects that of higher energies which depend on a spectral index of gamma-ray energy primaries. The fraction of EHE gamma-rays above $10^{19}$eV yields an upper limit of 32% at 90% CL for the proton+gamma-ray combination. For the iron+gamma-ray, the fraction is $31^{+16}_{-11}\%$. Super- and subscripts denote upper and lower bounds at 90% CL. Corresponding intensities are $< 5.3 \times 10^{-15}$[1/m$^2$ s sr] and $5.1^{+2.6}_{-1.1} \times 10^{-15}$[1/m$^2$ s sr], respectively. An upper limit of the EHE gamma-ray intensity at $10^{19.5}$eV is estimated to be 50% for that of proton+gamma-ray combination.

## 5 Discussion

### 5.1 Individual Super-GZK events

Super-GZK events observed by AGASA are discussed in this Proceedings (Sakaki, *et al.* (2001); Takeda, *et al.* (2001)). The significant event clusters above $4\times10^{19}$eV events are reported which suggest a possible presence of neutral particles from compact sources. As seen in Figure 2, such highlighted Super-GZK events seem to be explained by hadronic showers. Therefore, there is no explicit indication of gamma-ray primaries at those energies .

### 5.2 Dependence on interaction models

We have tested observable properties of EHE gamma-ray initiated showers using MC. For an experimental threshold energy (0.5GeV$\times \sec\theta$), the observed muon component is derived from interactions at very high energies. Under the photonuclear interaction modeled in EGS4 package (Nelson, Hirayama and Rogers (1985)), which is employed by AIRES, there are less muons in gamma-ray showers component than in hadronic ones. Note that there are claims on a contents of photoproduced muons in gamma-ray initiated showers (*Eg.* Aharonian, Kanevsky and Sahakian (1991)). The muon content in hadronic showers also depends upon interaction models used. Therefore a detailed test of interaction models is required by means of both simulations and experiments in future.

### 5.3 Fraction of EHE gamma-rays

A fraction of gamma-rays around $10^{19}$eV is a realistic threshold energy to test models of the origin of the highest energy cosmic rays with present data. The deduced intensity at an estimated energy depends on that at a higher primary energy. The enhancement factor to convert to primary energy is 20% for the typical gamma-ray differential spectral index of $\sim -1.5$ predicted by Top-Down scenarios. Under Top-Down scenarios, primaries of heavy nuclei are not expected. The intensity for the proton+gamma-ray primary combination gives a relevant constraint to such models. As mentioned above, the fraction upper bound of EHE gamma-ray is $32\%$ above a primary energy $\sim 10^{19}$eV. Since Top-Down scenarios predict much lower gamma-ray flux around $10^{19}$eV than the present upper limit, this result gives no strong constraints against such models.

## 6 Conclusion

We have searched for EHE gamma-ray initiated showers with AGASA muon data. Assuming QGSJET interaction models, $\rho_\mu(1000)$ distribution obtained by AGASA is explained by a mixture of hadron and gamma-ray primaries. The contribution of gamma-ray primaries is permitted up to 32% at 90%CL if hadronic primaries are all protons. Hence typical Top-Down models may not be ruled out by the present results.

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