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Energy estimation of AGASA events

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

[1]RIKEN (The Institute of Physical and Chemical Research), Wako 351-0198, Japan
[2]Department of Physics, Kinki University, Osaka 577–8502, Japan
[3]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277–8582, Japan
[4]Faculty of Engineering, Yamanashi University, Kofu 400–8511, Japan
[5]Department of Physics, Saitama University, Urawa 338–8570, Japan
[6]Faculty of Engineering, Musashi Institute of Technology, Tokyo 158–8557, Japan
[7]Department of Physics, Tokyo Institute of Technology, Tokyo 152–8551, Japan
[8]Nishina Memorial Foundation, Komagome, Tokyo 113-0021, Japan
[9]Faculty of Science and Technology, Hirosaki University, Hirosaki 036–8561, Japan
[10]Department of Physics, Osaka City University, Osaka 558–8585, 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. We have observed cosmic rays above 10^{20} eV by the Akeno Giant Air Shower Array (AGASA). Their energy determination is important to discuss their origin. In this paper, energy estimation method of the AGASA events at various zenith angles is described up to $60°$ and the experimental results are reproduced by the simulation taking into consideration the response of the detector. A new conversion relation to estimate the primary energy is obtained.

Grand Unified Theory (GUT) scale and to be hard, $\sim E^{-1.5}$ and gamma-rays may be dominant (Bhattacharjee and Sigl, 2000). In any case, in the energy spectrum there will be a cut off (GZK cut off) around 4×10^{19}eV if sources are extragalactic origin and distributed uniformly in the universe. If the special relativity is violated (Coleman and Glashow, 1999), the energy of the GZK cut off will be higher or disappear. Therefore energy estimation of the ultra-high energy cosmic rays is very important to reveal their origin.

1 Introduction

Cosmic rays above 10^{20}eV were observed by the Akeno Giant Air Shower Array (Takeda *et al.*, 1998). The source candidates of these ultra-high energy cosmic rays are classified into two models, the bottom-up model and the top-down model. In the bottom-up model, charged particles are accelerated in astrophysical objects and propagate to the earth through intergalactic and galactic space. The acceleration limit at astrophysical objects is considered to be around 10^{20} to 10^{21}eV(Nagano and Watson, 2000). In the top-down model, ultra-high energy cosmic rays are produced as decay products of heavy particles generated in the early universe. Their energy spectrum is considered to extend up to

2 Experiment

AGASA is located at $35°47'$N, $138°30'$E. The height of the central observatory is 900m (atmospheric depth 920g/cm^2). 111 scintillation detectors are deployed over an area of 100km^2 with a separation of about 1km. A scintillator of 5cm thickness and of 2.2m^2 area is installed in a steel box. The pulse height of each signal and its counting rate of each scintillation detector are continuously monitored independent of shower triggers and the monitor data is used for calibration of absolute number of particles.

The method of estimating energy in the AGASA experiment is briefly outlined as follows.

Correspondence to: N. Sakaki (n-sakaki@riken.go.jp)

1. The density observed at each detector is fitted by an em-

pirical formula.

$$\rho(r) = C\left(\frac{r}{R_M}\right)^{-1.2}\left(1+\frac{r}{R_M}\right)^{-\eta+1.2}$$
$$\times \left\{1+\left(\frac{r}{1[\text{km}]}\right)^2\right\}^{-0.6}, \qquad (1)$$
$$\eta = 3.97 - 1.79(\sec\theta - 1), \qquad (2)$$

where r is the distance from the shower axis, C is the normalization factor, R_M is the Moliere Unit at Akeno (91.6m) and θ is zenith angle. The local density at 600m from the shower axis of the shower with θ, $S_\theta(600)$, is obtained.

2. For inclined showers, the densities attenuate because they pass through more atmosphere than for vertical showers. $S_\theta(600)$ is converted to $S_0(600)$ using the attenuation length determined by experiment.

3. The primary energy is estimated using the relation between $S_0(600)$ and energy determined by a Monte Carlo simulation.
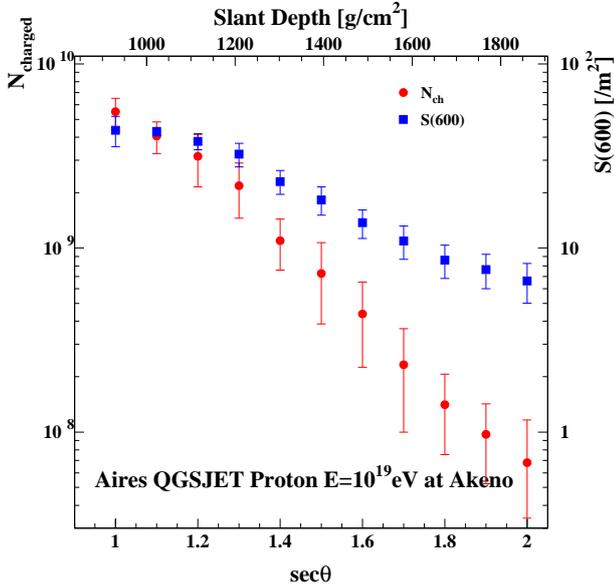

Fig. 1. Attenuation of total number of charged particles(N_{ch}) and $S(600)$ as a function of $\sec\theta$.

We have used $S_0(600)$ as an energy estimator. Fig.1 shows the comparison of attenuation in the atmosphere between $S_\theta(600)$ and the total number of charged particles, N_{ch}. The fluctuation of $S_\theta(600)$ is smaller than that of N_{ch} and attenuates more slowly. Therefore we use $S_\theta(600)$ as an energy estimator, whose effectiveness was first proposed by Hillas *et al.* (1971). The fluctuation of density at 600m is also shown to be small by Dai *et al.* (1988).

The conversion factor from $S_0(600)$ to the primary energy at the Akeno level was derived by the simulation (Dai *et al.*, 1988) based on the COSMOS program by Kasahara *et al.* (1979) and the following relation has been used for AGASA experiment so far.

$$E_0\,[\text{eV}] = 2.03 \times 10^{17} \cdot S_0(600)^{1.0} \qquad (3)$$

In the simulation, the density was calculated by adding the densities from electron sub showers, which were approximated by the NKG function. Therefore the observed density was converted to electron density to compare with the simulated one as described in Nagano *et al.* (2000). In this paper, considering the structure of the AGASA detector, the density observed with the scintillator is evaluated, by Monte Carlo simulation, which can be directly compared with the experimental data.

3 Monte Carlo simulation

3.1 Detector

The response of the AGASA detector is evaluated using GEANT3.21. Each scintillator of 2.2m^2 area and 5cm thickness is installed in the box made of 2mm thick steel, which is settled in a hut made of 0.4mm thick steel. The conversion of photons in the wall of the hut and of the scintillator box, the scattering of particles, the decay of unstable particles etc. and 4-momentum of shower particles are taken into account. The energy deposit in the scintillator is taken as the signal from the detector.

Fig.2 is the response of the AGASA detector to photons, electrons and muons with various energies and incident angles. In the energy spectrum of shower particles, the mean energies of photons and electrons are ~ 10MeV and that of muons is ~ 1GeV around 1km from the shower core. Therefore photons typically contribute as ~ 0.1 particles, and electrons and muons typically contribute as one particle. These three particles are major particles in air showers, though the response to other particles such as pions and kaons are also taken into account.

In the AGASA experiment, "one particle" is defined conventionally as a peak value of the pulse width distribution (PWD). In the simulation, "one particle" is defined as the peak value of $\log_{10}(\text{Energy deposit in the scintillator})$ for omni-directional muons taking the energy spectrum into consideration like the experiment.

3.2 Air Shower

AIRES 2.2.1 (Sciutto, 1999) was used to generate air showers for proton and iron primaries at a thinning level of 10^{-6}. As the hadron interaction models in the high energy region, QGSJET and SIBYLL are used. The results of four combination of different primary particles and different interaction models are compared. Each shower particle generated by AIRES is converted to scintillator response using the results
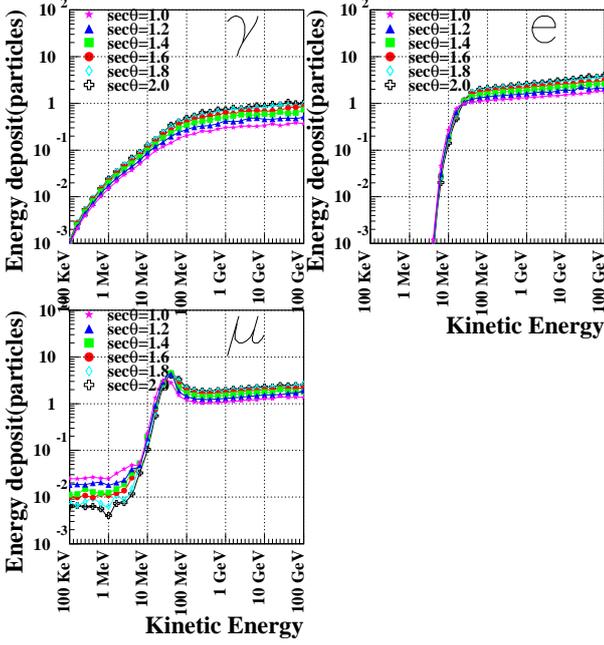
Fig. 2. The simulated distribution of energy deposit in the scintillator of AGASA detector. The energy deposit is converted to the number of particles using the definition in the text. Top left panel for gamma-ray, top right for electron and bottom left for muon with various incident angles.

described in the previous section taking into account the incident angle and the energy of each particle.

4 Results

The attenuation of $S(600)$ with atmospheric depth is determined using the equi-intensity cut method. In this method, assuming the intensity of the cosmic rays is independent of the zenith angle, the equi-intensity cut is made on the integral spectra of $S_\theta(600)$ at various zenith angles. The results are plotted in Fig.3. These plots correspond to the attenuation of $S_\theta(600)$ at a certain energy. The dashed lines (b) in the figure is the empirical function we have used for AGASA so far, and it is valid up to $\sec\theta \sim 1.5$. This empirical function is extended in order to use the events up to $60°$ and a new function is shown by solid lines (a) in the figure. This relation is expressed by the following equation.

$$
\begin{aligned}
S_\theta(600) &= S_0(600)\exp\left[-\left\{\frac{X_0'}{\Lambda_1'}(\sec\theta - 1)\right\}\right.\\
&\quad -\left\{\frac{X_0'}{\Lambda_2'}(\sec\theta - 1)\right\}^2\\
&\quad \left.+\left\{\frac{X_0'}{\Lambda_3'}(\sec\theta - 1)\right\}^3\right],
\end{aligned}
\tag{4}
$$

where $X_0' = 957\text{g/cm}^2$ is the average atmospheric depth at
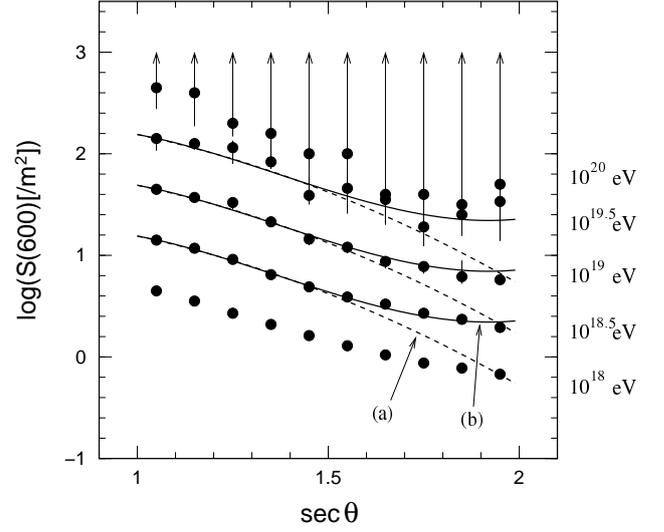

Fig. 3. Attenuation of $S(600)$ using the equi-intensity method. The closed circles are experimental data. The dashed lines (a) represent the equation which has been used for the AGASA experiment so far, and the solid lines (b) represent the newly obtained function (Equation(4)), which agree well with experimental data up to $60°$.

AGASA, $\Lambda_1' = 605\text{g/cm}^2$, $\Lambda_2' = 514\text{g/cm}^2$ and $\Lambda_3' = 654\text{g/cm}^2$.

The equation(4) agrees well with the experimental data up to 10^{20}eV, although the error becomes large around 10^{20}eV.
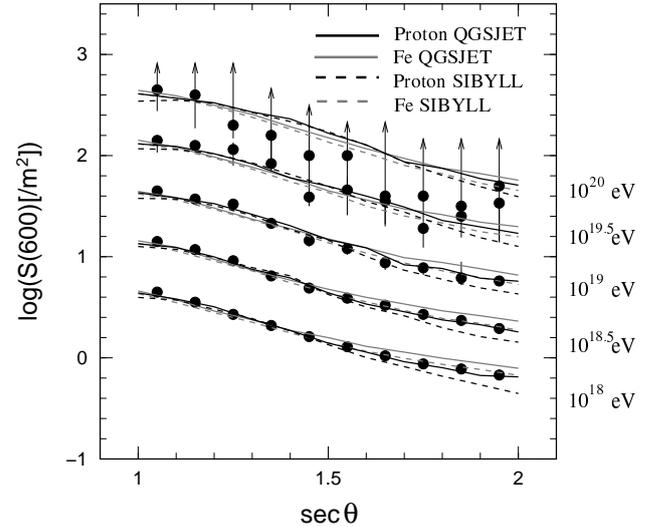

Fig. 4. The attenuation of $S_\theta(600)$ by experiment compared to that by AIRES simulation. The black lines and the gray ones are proton and iron primary cosmic rays, respectively, and the solid and dashed lines are the results using QGSJET model and SIBYLL model, respectively.

$S_\theta(600)$ determined using experimental data and that using simulated data are compared in Fig.4. The results calculated by AIRES simulation agree well with the experimental data. The difference between the primary particles, pro-

ton and iron, and between the hadronic interaction models, QGSJET and SIBYLL is less than 10 % up to $\sec\theta = 1.5$ and 20 % around $\sec\theta = 2$.
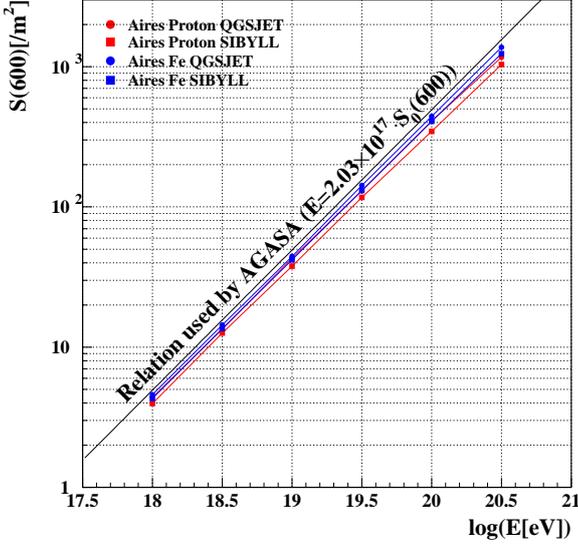
5 Energy conversion relation

Fig. 5. The relation of $S_0(600)$ parameter and primary energy for proton (red) and iron (blue) obtained by AIRES simulation. QGSJET (circle) and SIBYLL (square) are used as interaction models at high energy.

Fig.5 shows the conversion relation from $S_\theta(600)$ to the primary energy for four combination of proton and iron primaries, and QGSJET and SIBYLL interaction models. When the relation is written with the following form, the parameters a and b are summarized in Table.1.

$$E_0\,[\mathrm{eV}] = a \times 10^{17} \cdot S_0(600)^b, \tag{5}$$

where $S_0(600)$ is in the unit of m^{-2}. The difference in energy conversion factor is about 10% at 10^{20}eV between proton and iron, and 10% between QGSJET and SIBYLL.

Table 1. The conversion relation of $S_0(600)$ to primary energy at average AGASA height calculated by AIRES.

model	spices	a	b
QGSJET	p	2.17	1.03
	Fe	2.15	1.01
SIBYLL	p	2.34	1.04
	Fe	2.24	1.02

The average conversion relation for primary proton and iron using the hadron interaction models, QGSJET and

SIBYLL is expressed by the following equation.

$$E\,[\mathrm{eV}] = 2.23 \times 10^{17} \cdot S_0(600)^{1.02}\,[\mathrm{/m}^2] \tag{6}$$

6 Summary

$S(600)$ is a more reliable energy estimator than the total number of charged particles at observation levels deeper than the depth at the shower maximum. Considering the scintillator response including the detailed structure of the AGASA detector the attenuation of $S_\theta(600)$ can be reproduced well by air shower simulations up to $60°$. As a consequence the sky near the Galactic center can be reliably covered by AGASA. It will be useful for the analysis of anisotropy related to our Galaxy. The $S_0(600)$-primary energy relation so far used for AGASA gives the more conservative energy than any of the simulation results performed this time. Using the new conversion relation to the primary energy, estimated energies of AGASA events is increased by 20% at 10^{20}eV.

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