The energy spectrum of primary cosmic rays obtained by using arrival time spread of air shower particles

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***Abstract*. We have been observed extensive air showers (EASs) with a compact EAS array which consists of 8 scintillation counters in $200\mathrm{m}^2$ area. In order to estimate the energy spectrum of primary cosmic rays by using the Linsley's method, a shift register system for recording the arrival time of EAS particles has been installed in an EAS array.**
By analyzing the observed data with this array from April 2006 to December 2008, The obtained primary energy spectrum consisted with the simulated one which is assumed to be the power law spectrum with the slop value of -3.0 in the primary energy range of $10^{16.0}$eV to $10^{18.0}$eV. Additionally, we report on the improvement of the determination accuracy of primary energy by applying the zenith angle restricted observation of EAS muons with a new array by the simulation.

***Keywords*: Linsley's method, EAS time structure, primary energy spectrum**

I. INTRODUCTION

Linsley suggested that the primary energy is able to be estimated by observing the arrival time spread of EAS particles, and then we can estimate the primary energy with a compact EAS array [1], [2].

The apparatus to record the arrival time information of EAS particles, which is called the shift register system, have been installed to the EAS array located at Okayama University of Science (OUS) in January 2006 [3], [4], [5], [6].

We have determined the zenith angle θ of EAS by fitting a plane to the shower front of the arrival time difference of EAS particles [3], [4], [5], but this method isn't available with increasing the arrival time spread of EAS particles, because a plane of the shower front can't be determined. Because Linsley's formula eq. 1 was obtained in averaging respect to the zenith angle of EASs up to 60 degree, we simulated EAS events up to the same angle of $60°$, which nominally came from our EAS array setting. Once, the primary energy estimate can be improved by obtaining information of zenith angle of EAS particles like muons.

II. APPARATUSES

The compact EAS array (OUS1) consists of 8 plastic scintillation counters (Fig. 1) and each counter is equipped with a scintillator, of which size and thickness are 50cm×50cm and 5cm respectively, and a fast photomultiplier. The scintillation counters are located over an area of about $200\mathrm{m}^2$.

The apparatus (OUS4) for obtaining zenith angle information of EAS particles has been installed in the building which is located about 10 m from the OUS1 (Fig. 1). The coincidence observation between the OUS1 and the OUS4 is carried out, and the time accuracy of coincidence observation between the OUS1 and the OUS4 is $1\mu\mathrm{s}$ with GPS modules. The OUS4 (Fig. 2) is equipped with plastic scintillation counters of which size and thickness are 50cm×50cm and 5cm on the side of oneself, and other plastic scintillation counters of which size and thickness are 40cm×50cm and 1cm on the top and bottom of oneself. Each EAS event is recorded when the triggered signals are occurred from top and bottom counters coincidentally. If only top and bottom counters are hit, zenith angle θ of the event is identified as $\theta \leq 45°$, and if even side counters are hit, it is identified as $\theta > 45°$.

Each triggered signal of scintillation counter is recorded with digital data which is converted from NIM to TTL by the shift register system, which is equipped with the OUS1 and the OUS4 respectively.

We are able to obtain the arrival time information of EAS particles with the time window of $\pm 2.5\mu\mathrm{s}$ and the time resolution of $5\mathrm{ns}$, because the shift register system is operated with a clock of 200MHz and the pulse width of the digitalized signal into the shift register system is $5\mathrm{ns}$.

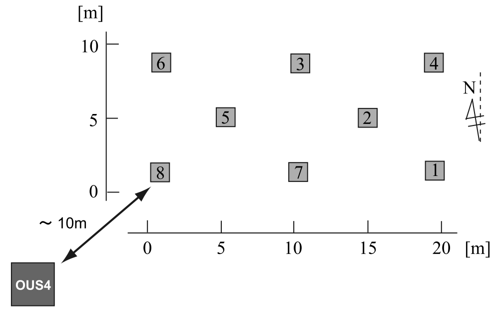

Fig. 1: Detector arrangement of the OUS1 array and the OUS4 array (top view). Numbered squares represent scintillation counters.

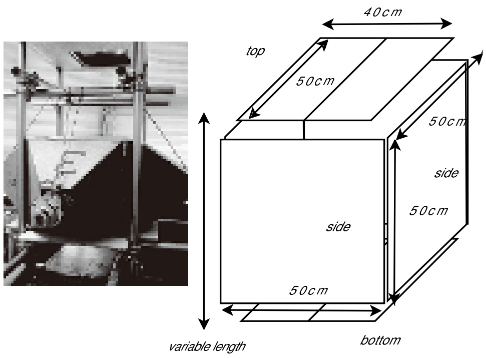

Fig. 2: The photo and the schematic diagram of the OUS4.

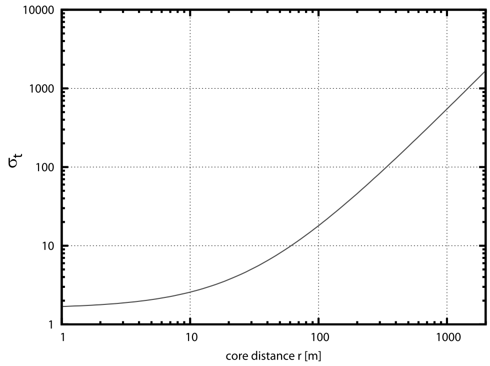

Fig. 3: The relation between the core distance and σ_t.

III. Data analysis and simulation

A. Estimation of core distance

The core distance r of EAS is calculated by the arrival time dispersion σ_{t} of individual EAS. The average arrival time dispersion $\langle\sigma_{\mathrm{t}}\rangle$ is able to be described by the empirical formula [1], [2],

$$\langle\sigma_{\mathrm{t}}\rangle \quad = \quad \sigma_{\mathrm{t}0}\left(1+\frac{r}{r_{\mathrm{t}}}\right)^{b}, \tag{1}$$

where $\sigma_{\mathrm{t}0} = 1.6\mathrm{ns}$, $r_{\mathrm{t}} = 30\mathrm{m}$ and $b \sim 1.65$. In the Fig. 3, σ_{t} is plotted as a function of r. The average dispersion doesn't depend on the primary energy.

The probability density function of the arrival time of EAS particles can be approximated by a gamma distribution, and then σ_{t} is calculated by

$$\sigma_{\mathrm{t}} \quad = \quad \frac{\sqrt{2}}{1.67}\mathrm{median}\,, \tag{2}$$

where the median is obtained by the arrival time distribution of EAS particles.

r is calculated by transforming eq.(1) and by eq.(2) as

$$r = 30\left\{\left(\frac{\sigma_t}{1.6}\right)^{(1/1.65)} - 1\right\}. \tag{3}$$

Events of which core distance r is determined as less than 100m, are not used in estimating the primary energies because σ_t is almost constant in the region of $r < 100\mathrm{m}$ and the relative error $\sqrt{\mathrm{var}\,(\mathrm{r})}/r$ is almost proportional to r^{-1}.

B. EAS simulation

We used the AIRES code [7] by making tables of the lateral distribution $\rho\,(r,\theta,E_0)$, the shower size $N\,(E_0,\theta)$ and the standard deviation of the shower size σ_N, where r, θ and E_0 is the core distance, the zenith angle and the primary energy, respectively. We assumed that the primary cosmic ray nuclei are protons. E_0 are sampled within $10^{16.0}\mathrm{eV}$ to $10^{20.0}\mathrm{eV}$ every order, and θ are also done from $0°$ to $60°$ every $10°$. The number of EAS events is 100 with each simulation.

Once these tables have been made, we calculated the EAS size $N'\,(E_0,\theta)$ and lateral distributions $\rho'\,(r,\theta,E_0)$ are evaluated without the AIRES code execution. The shower size $N'\,(E_0,\theta)$ are parameterized as $N\,(E_0,0)\cos\left(\mathrm{C}\theta^{\mathrm{a}}\right)$, where a and C are fitting parameter, respectively. The correlation between EAS size $N\,(E_0,\theta)$ and its dispersion σ_N are used to consider $N\,(E_0,\theta)$ fluctuations.

The detector simulation is carried out with each E_0. r and θ are sampled by using a random number in the region of $0\mathrm{m}$ to $2000\mathrm{m}$ and a random number of $\sin\left(\theta\right)$, respectively. Each of θ in the OUS1 and the coincident observation between the OUS1 and the OUS4 (OUS1+OUS4) is within $60°$ and $45°$. The number of particles triggered with each detector located at r is sampled by using the table of $\rho\,(r,\theta,E_0)$ and a Poisson random number.

The arrival time of each triggered EAS particles is sampled by using a gamma distributed random number, and its median is calculated from the arrival time distribution obtained by summing up triggered particles in all scintillation counters. However, the trigger criterion of EAS event is that at least 3 scintillation counters are hit within $2.5\mu\mathrm{s}$, and the effective time width is $\pm 2.5\mu\mathrm{s}$ from the triggered time in the OUS1.

Additionally, we consider the contamination of chance coincidence in the detector simulation. The chance coincidence is assumed to be random noises like atmospheric muons or the thermal noise of the scintillation counter. One chance coincidence is generated with a random number in the time window of $\pm 2.5\mu\mathrm{s}$ and is added to EAS particles.

We can obtain ρ' which is calculated from the total

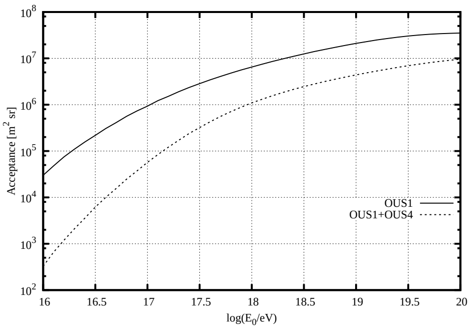

Fig. 4: The acceptance of the OUS1(solid line) and the OUS1+OUS4(dash line).

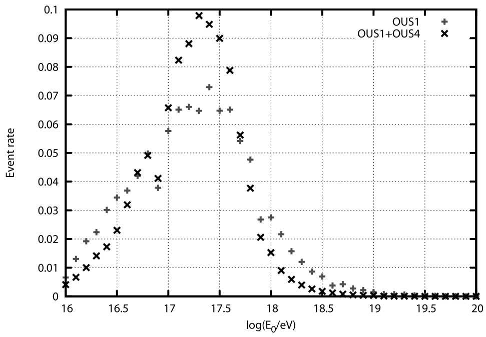

Fig. 5: The simulated primary energy distribution of the OUS1 and the OUS1+OUS4 at $E_0 = 10^{17.5}$eV.

number of particles and the detector area of $1.75\mathrm{m}^2$, and r' which is recalculate by using eq.(1), eq.(2) and the obtained median. The evens of r'<$100\mathrm{m}$ and $\mathrm{median}'/\mathrm{median}$<$0.4$, where median' is calculated the median by excluding the first arrival particles in obtained ones, aren't use the primary energy estimation. The lateral distribution is averaged by using the zenith angle distribution which is detected by the OUS1 in the simulation with each E_0.

Hence, the primary energy is estimated from the table of the simulated lateral distribution by using ρ' and r'. And, r' and ρ' can be obtained in the observation.

C. Primary energy spectrum

We assume the power law spectrum $f(E_0) = E_0{}^{\alpha}$, where the slop value $\alpha = -2.0, -2.5, -3.0$. The primary energy spectrum simulated with each observation is defined as $f'(E_0)$, $f'(E_0)$ is calculated by taking account of the acceptance (Fig. 4) and by the convolution with simulated each primary energy distribution of the OUS1 (Fig. 5).

D. Data set

In the OUS1 observation, the data period used for this analysis is from April 2006 to December 2008, and the observation time is 670 days. Total number of events is about 4×10^6 events and about 5×10^4 events were able to estimate their primary energy.

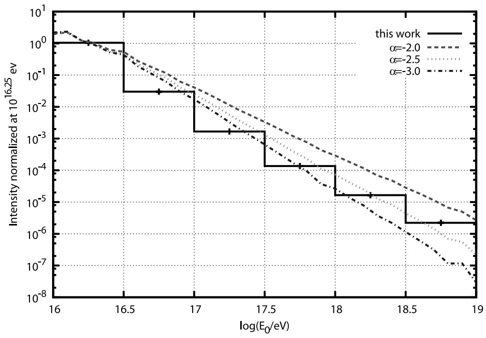

Fig. 6: The comparison of data with simulation. The histogram and lines represent the data and the simulation, respectively. $\alpha = -2.0, -2.5$ and -3.0 are a dash line, a dot line and a dash-dot line, respectively.

IV. Result

The comparison of the obtained primary energy spectrum with the simulated ones is represented in the Fig. 6. In the primary energy range of $10^{16.0}\mathrm{eV}$ to $10^{18.0}$eV, the obtained slop value is -2.6 by fitting. α' defined as the obtained slop value of the primary energy spectrum in the simulation, was obtained as $-2.0, -2.4$ and -2.6 with $\alpha = -2.0, -2.5$ and -3.0, respectively. Then, the slop value obtained by analyzing data agrees with the slop value assumed to be -3.0 in the simulation.

In the primary energy region above 10^{18}eV, the obtained primary energy spectrum became flatter. Because the width of primary energy distribution becomes large with increasing the primary energy, the obtained energy spectrum tend to be overestimated with increasing the primary energy.

On the other hand, due to the contamination of chance coincidence of random noises, the slop value is overestimated. The probability of chance coincidence in the OUS1 is 10^{-3}, and then 0.1 percent of total number of events are overestimated their primary energy.

V. Discussion

Due to the energy resolution of the OUS1, each spectrum ratio $f'(E_0)/f(E_0)$ obtained the OUS1 is overestimated with decreasing α in Fig. 7. For the improvement of the OUS1's energy resolution, we remove EASs with large zenith angle by using the OUS4. The simulated energy distribution by the OUS1 and the OUS1+OUS4 at $E_0 = 10^{17.5}$eV are indicated in Fig. 5. In the comparison between the full width at half maximum of the OUS1 and that of the OUS1+OUS4, the latter ($10^{16.9}$ to $10^{17.7}$eV) is smaller than the former ($10^{16.6}$ to $10^{18.9}$eV). Hence, $f'(E_0)/f(E_0)$ in the OUS1+OUS4 is obtained with $f'(E_0)/f(E_0) \sim 1$ in Fig. 7. Each α' was obtained as $-2.3, -2.7$ and -3.0 with $\alpha = -2.0, -2.5$ and -3.0 in the primary energy range of $10^{16.0}\mathrm{eV}$ to $10^{18.0}\mathrm{eV}$.

And the chance coincident is able to be reduced by the coincidence observation of the OUS1 and the OUS4. The probability of chance coincident in the OUS1+OUS4 is

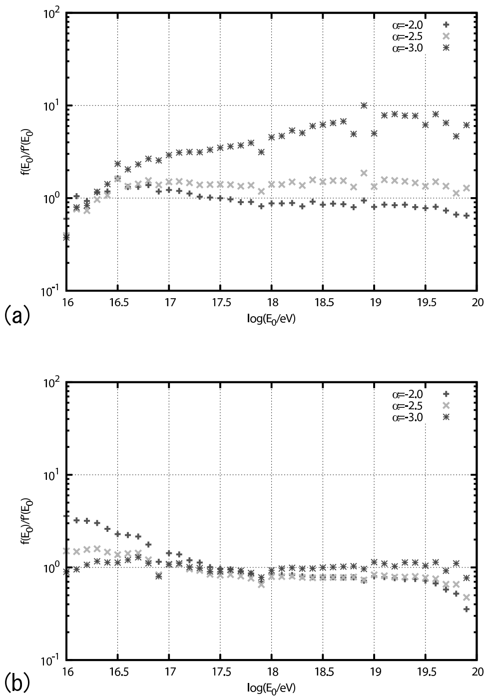

Fig. 7: (a) and (b) are simulated spectra ratios in case of using the OUS1 and the OUS1+OUS4.

10^{-6}, and the chance coincident of the OUS1+OUS4 is 10^3 times less than that of the OUS1. By decreasing the chance coincidence, the overestimation of the slop value is able to be suppressed in the region above $10^{18.0}$eV. For this reason, the determination accuracy of primary energy spectrum can be improved by decreasing the chance coincidence.

VI. Conclusion

We have observed EASs and estimated the primary cosmic ray energy and spectrum in the energy region above $10^{16.0}\mathrm{eV}$ with the compact EAS array by using the Linsley's method. The obtained primary energy spectrum agrees with simulation in the case of $\alpha = -3.0$ in the primary energy region of $10^{16.0}\mathrm{eV}$ to $10^{18.0}$eV.

And we presented that the determination accuracy of primary energy spectrum above $10^{18.0}\mathrm{eV}$ can be improved by restricting the zenith angle obtained with the OUS4. The OUS4 has been installed in August 2008, and the coincident observation of the OUS1 and the OUS4 has been carried out since then.

References

[1] J.Linsley, *Proc. 19th ICRC, La Jolla*, **3**, (1985) 434.
[2] J.Linsley, *J. Phys. G: Nucl. Phys.*, **12**, (1986) 51.
[3] T.Wada et al., *Nuclear Physics B (Proc. Suppl.)* **75A** (1999) 330-332
[4] N.Ochi et al., *J. Phys. G: Nucl. Part. Phys.* **29** (2003) 1169-1180
[5] A. Iyono et al., *Nucl. Phys. B (Proc. Suppl.)*, **151**, (2006) 69
[6] M.Okita et al., *Nuclear Physics B (Proc. Suppl.)* **175-176** (2008) 322-325
[7] S.J.Sciutto, *astro-ph/9911331* (1999); http://www.fisica.unlp.edu.ar/auger/aires