Linsley's EAS time structure method for the primary cosmic ray spectrum at LAAS

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Abstract

A compact extensive air shower (EAS) array of eight plastic scintillation counters covering a total area of 2m^2 is built in Okayama University of Science, and operated since April 2006. We have also performed detector simulations based on the database obtained from the AIRES simulator and developed the procedures to estimate the primary cosmic ray energy from Linsley's time structure method. Applying this method to our EAS data and the simulation result, we derived the energy spectrum from 10^{16} to $10^{19.5}$eV, and obtained the power-law index of -3.2(+0.46 -0.8) in the primary energy range of 10^{16} to $10^{18.5}$eV. Additionally, we also showed the improvement of energy resolution by applying the ristriction of zenith angle of primary cosmic rays in our simulation.

1.Aims

The estimate of the primary energy spectrum by using Linsley 's EAS time structure method with a compact EAS array.

2.Apparatus

OUS1

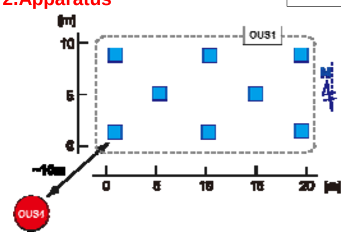

Fig.1 The layout of the OUS1 array. The blue square symbols represent scintillation counters in the OUS1 array. The circle painted in red indicate the location of the OUS4 array

•Detector

- •Plastic scintillation counter (50cm × 50cm × 5cm, PMT:HAMAMATSU H7195)

•Data acquisition system

- •ADC (Lecroy 2249W), TDC (Kaizuworks 3781), GPS module (Kaizuworks 3051A)
- •Shift register (MPK NIM-ANY)

•Trigger condition

- •More than 3 detectors (within 2.5 μ s time window)

•Array size

- •~200m^2

•Location

- •Okayama University of Science, 34° 42' N, 133° 56' E

OUS4

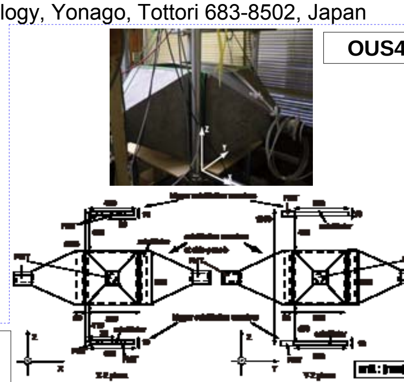

Fig.2 The OUS4 array and its X-Z and Y-Z views.

•Detector

- •Plastic scintillation counter (50cm × 50cm × 1cm, PMT:HAMAMATSU R594-1, top and bottom layer)
- •Plastic scintillation counter (50cm × 50cm × 5cm, PMT:HAMAMATSU H7195, side layer)

•Data acquisition system

- •ADC (Lecroy 2249W), TDC (Kaizuworks 3781), GPS module (Kaizuworks 3051A)
- •Shift register (MPK NIM-ANY)

•Trigger condition

- •Detectors of top and bottom layer (within 2.5 μ s time window)

•Time Accuracy of the coincidence observation the OUS1 and the OUS4

- •~1 μ s

•Zenith angle restriction

- • θ < 25.6deg.

•Location

- •Indoor installation (first floor of a four stories building)
- •~10m distance from the OUS1

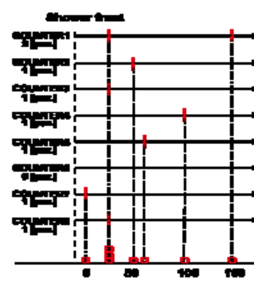

Fig.3 The concept of EAS particle arrival timing at each scintillation counter recorded by the shift register.

The shift register system:

The shift register system can record arrival time information of EAS particles by each detector within the time window 2.5 μ s from the trigger time. Each signal of detectors is digitized with the shift register system with the time resolution of 5ns (operating clock : 200MHz).

3.Linsley's method

The individual EAS thickness is defined by using the dispersion σ_t of arrival time distribution of EAS particles. The average behavior of dispersion $<\sigma_t>$ can be described by empirical formula

$$\langle\sigma_t\rangle = \sigma_{t0}\left(1+\frac{r}{r_t}\right)^b ,$$

$$b = (2.08\pm0.08)-(0.4\pm0.06)\sec\theta+(0\pm0.06)\log(E_0/10^{17}\mathrm{eV}) ,$$

where r is the core distance of EAS, σ_{t0}=1.6ns, r_t=30m, and b as function the EAS zenith angle θ and the primary energy E, as shown in Fig. 4. However, we used the averaged b value (b=1.65) instead of the original b.

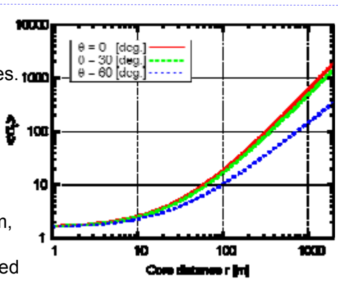

Fig.4 $<\sigma_t>$ of arrival time distribution of EAS particles as a function of EAS core distance r.

The probability density function of EAS particle arrival time can be approximated by a gamma distribution, and then σt is calculated by

$$\sigma_t = \frac{\sqrt{2}}{1.67}t_{\mathrm{median}} ,$$

where t_{median} is the median in the series of EAS particle arrival time. The core distance r is calculated as

$$r = 30\left\{(1.35t_{\mathrm{median}})^{1/1.65}-1\right\} .$$

4.Simulation

1. We made databases of the lateral distribution of electrons and muons, the number of electrons and muons, and the standard deviation of the number of electrons by using AIRES simulator.
2. We carried out the detector simulation for arbitrary primary energy in order to make databases of the lateral distribution averaged by simulated zenith angle distribution.
3. The primary energy resolution functions is calculated by using 1 and 2.
4. The observed energy spectra are the convolution of the assumed power-law spectra with the acceptance and primary energy functions obtained by 3.

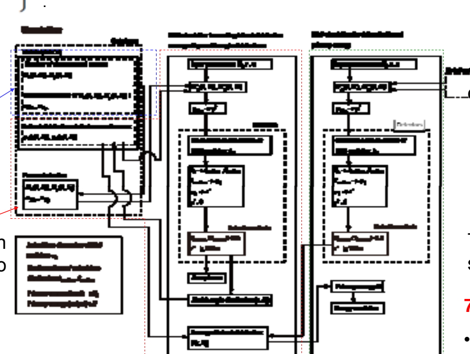

Fig. 5 The diagram of simulation procedure.

The configuration of simulation parameters

- •Hadronic interaction model: QGSJETII-3 + Hillas Splitting Algorithm
- •The primary cosmic ray: proton, E0 =10^{16}eV ~ 10^{20}eV
- •The zenith angle θ : 0deg. ~ 60deg
- •The core distance r : 0m ~ 2000m
- •The chance coincident which is assumed to be random noises like atmospheric muons or the thermal noise of the scintillation counters.

5.Result

We analyzed the OUS1 data obtained from April 2006 to December 2008, and the observation time is 670 days. Total number of observed events is about 4 × 10^6 and about 5 × 10^4 events can be used to estimate their primary energy.

The obtained energy spectrum is shown in the Fig. 6. α' is the obtained spectral index and α is the spectral index which is corrected with the energy resolution of the OUS1. The fitting performed with the least square fitting method. The obtained data spectrum is fitted by s single power-law spectrum $E_0^{\alpha'}$. α' and α are summarized in the Table 1.

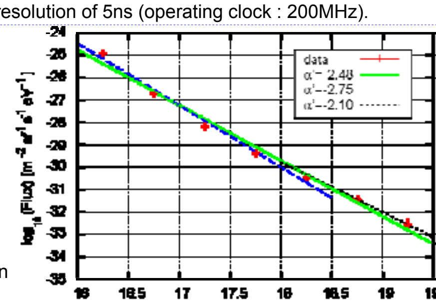

Fig.6 The primary energy spectrum obtained by the OUS1.

Table 1 α' and α.

Primary energy range [eV]	α'	α
$10^{16} \sim 10^{19.5}$	-2.48 ± 0.12	$-2.55\,(+0.19\ -0.25)$
$10^{16} \sim 10^{18.5}$	-2.75 ± 0.17	$-3.20\,(+0.46\ -0.80)$
$10^{18} \sim 10^{19.5}$	-2.10 ± 0.08	$-2.00\,(+0.12\ -0.11)$

6.Discussion

•The flattering of the obtained primary energy spectrum in the primary energy region of 10^{18} – $10^{19.5}$eV.

→Due to the energy resolution of the OUS1 (Fig. 7).

•The improvement of the primary energy resolution.

→It can be done by restricting the EAS zenith angle by using OUS4 (Fig. 8 and 9).

The determination accuracy of the spectral index can be improved (Fig 10).

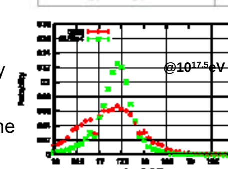

Fig.7 The simulated primary energy distribution of the OUS1 and OUS1+4.

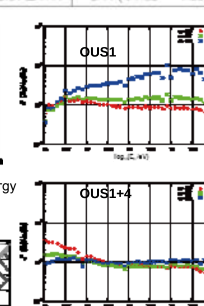

Fig.8 Simulated spectrum ratios in case of using the OUS1 and the OUS1+4.

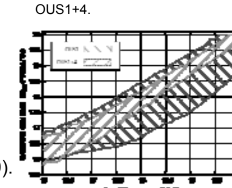

Fig.8 The energy resolution as a function of primary energy..

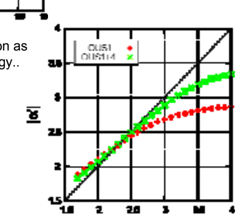

Fig.10 The comparison between the indices of the primary energy spectra and obtained ones.

7.Conclusion

•We have obtained the primary energy spectrum in primary energy region of 10^{16} – $10^{19.5}$eV by using the Linsley's method with the compact EAS array "OUS1". The spectral index α is equal to α=-3.2(+0.46 – 0.8) in the primary energy region of 10^{16} -$10^{18.5}$eV.

•In order to improve the energy resolution of the OUS1, we have simulated the improvement of the determination accuracy of the primary energy spectrum by using the OUS4 and have installed the OUS4.