JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN Vol. 17, SUPPLEMENT A-III, 1962
INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part III

III-4-11. Experimental Data on Development of Extensive Air Showers in Upper Atmosphere

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Air showers at altitudes of 6, 4, 9 and 12 km have been investigated[1] by means of counter hodoscopes and ionization chambers.

The diagram of the apparatus is presented in Fig. 1. The density of each shower was measured in three hodoscopic points. At a central hodoscopic point two groups of counters were used (in each group there were 40 counters with dimensions $30\times300\,\mathrm{mm}^2$). In

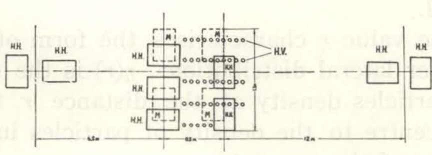

Fig. 1. The plan of the apparatus. H.H.-Set of horizontal hodoscopic counters. H.V.-"Vertical" hodoscopic counters. M.-Master counters.

one of these groups the counters were oriented horizontally and in the other vertically. Counters were located with intervals equal to a counter's diameter. Horizontally oriented counters were divided into two groups differing by the direction of the counter axes. These directions were mutually perpendicular. Two other hodoscope points were disposed at 8 and 12 m from the centre of the apparatus (in each point there were 20 counters with dimensions $30\times300\,\mathrm{mm}^2$).

All counter hodoscopes worked in a regime of controlled pulse power supply. The control pulse was supplied to counter hodoscopes when four groups of counters were discharged simultaneously. The area of each group was $86\,\mathrm{cm}^2$. Control counters were located immediately below counter hodoscopes of the central hodoscopic point.

The apparatus made it possible to select showers whose axes were close to vertical, as when the apparatus registers shower incident at small zenith angles the number of discharging vertical counters is statistically lower than the number of discharging horizontal counters.

If n horizontal counters discharge (from total number N) then in accordance with the Bayes theorem the probability that the value of the shower density near the apparatus will be ρ is

$$W\left(\frac{\rho\sigma_{\mathrm{horis}}}{n}\right)=\frac{\rho^{-\gamma}\cdot C_N^n\cdot(1-e^{-\rho\sigma_{\mathrm{horis}}})^n\cdot e^{-\rho\sigma_{\mathrm{horis}}\cdot(N-n)}}{\int_0^\infty\rho^{-\gamma}\cdot C_N^n\cdot(1-e^{-\rho\sigma_{\mathrm{horis}}})^n\cdot e^{-\rho\sigma_{\mathrm{horis}}\cdot(N-n)}\,d\rho} \tag{1}$$

If the shower density near the apparatus is ρ the probability that m counters will discharge (from total number N of vertical counters) can be expressed as:

$$W\left(\frac{m}{\rho\sigma_{\mathrm{vert}}}\right)=C_N^m\cdot(1-e^{-\rho\sigma_{\mathrm{vert}}})^m\cdot e^{-\rho\sigma_{\mathrm{vert}}\cdot(N-m)} \tag{2}$$

Hence when n horizontal counters discharge the probability that for the shower at the zenith angle θ m "vertical" counters will discharge is as follows:

$$W\left(\frac{m}{n},\theta\right)=\int_0^\infty W\left(\frac{\rho\sigma_{\mathrm{horis}}}{n}\right)\cdot W\left(\frac{m}{\rho\sigma_{\mathrm{vert}}}\right)d\rho\,, \tag{3}$$

where

$$\sigma_{\mathrm{vert}}=\sigma_{\parallel}\cdot\sin\theta+\sigma_{\perp}\cdot\cos\theta\,, \tag{4}$$

$$\sigma_{\mathrm{horis}}=\left(\frac{\sigma_{\parallel}}{\sqrt{2}}\cdot\sqrt{1+\cos^2\theta}+\sigma_{\parallel}\right)\cdot\frac{1}{2} \tag{5}$$

The counting rate of the showers in which n "horizontal" and $m\leqq m'$ "vertical" counters discharged may be presented in the form:

$$\mathrm{N}(n,m\leqq m')=\int_0^{\pi/2}\frac{dN(r,t,\theta)}{d\theta}\cdot\sum_{m=0}^{m'}W\left(\frac{m}{n},\theta\right)2\pi\sin\theta d\theta \tag{6}$$

The showers whose axes are close to vertical may be selected and the intensity of the vertical showers stream may be computed

Table I

Altitude	Time Measured (Hours)	η	The Total Number of Showers Recorded			The Number of Selected Showers		
			$15\le n\le 19$ 45 m^{-2}–65 m^{-2}	$20\le n\le 25$ 70 m^{-2}–100 m^{-2}	$26\le n\le 37$ 110 m^{-2}–275 m^{-2}	$15\le n\le 19$ 45 m^{-2}–65 m^{-2}	$20\le n\le 25$ 70 m^{-2}–100 m^{-2}	$26\le n\le 37$ 110 m^{-2}–275 m^{-2}
Sea level 1,030 g/cm^2	64.4	η(8m) and η(12m)≤ 0.3 η(8m) or η(12m)>0.3	32 89	22 42	10 36	10 18	8 17	4 19
4.4 km 597±4 g/cm^2	0.40	≤ 0.3 >0.3	5 15	3 9	0 7			
6.4 km 455±3 g/cm^2	5.37	≤ 0.3 >0.3	101 327	54 197	47 157	12 28	10 32	23 33
7.47 km 392±3 g/cm^2	1.62	≤ 0.3 <0.3	21 119	19 78	18 54			
9 km 311±2 g/cm^2	13.1	≤ 0.3 >0.3	384 839	215 535	209 528	61 71	59 90	69 62
12 km 497±1 g/cm^2	8.97	≤ 0.3 >0.3	399 398	215 251	166 183	80 26	75 32	47 23

using the formula (6) if n and m were determined in the experiment.

The similar calculations may be carried out with taking into account the particle scattering due to which the directions of shower particle are distributed in respect with the direction of the shower axis according to Gauss law.

In calculation according to the formula (6) we have used as the first approximation an angular distribution obtained by the application of Gross's generalized transformation[2)3)] to the altitude dependences of the rates of all showers recorded by our apparatus. m' was chosen in such a way that not less than 75% of showers selected had the zenith angle $\theta<30°$. It turned out that m' values are close to the value $1.04\times m-11$. When $n>15$ the number of showers selected practically does not depend on the form of the angular distribution of showers. The calculation was performed for three values of the mean-square scattering angle 0°, 15° and 30°.

To control the method ground measurements were carried out. Experimental data agree with the angular distribution of extensive air showers at sea level $dN(\theta)/d\theta\sim\cos^8\theta$ with the value of the mean-square scattering angle 15–20°. Such value of the scattering angle follows from the calculations according to the cascade theory[4)5)] and is confirmed by the experiment[6)7)].

In Table I initial experimental results are listed.

The value η characterises the form of the shower lateral distribution: $\eta(r)$ is the ratio of particles density at the distance r from the centre to the density of particles in the centre of the apparatus.

The selection of showers with $\eta<0.3$ makes it possible to consider separately such showers in which due to sharp lateral distribution the total number of particles in a shower is not great. Evaluations made according to the cascade theory have shown that with $\eta>0.3$ the energy of particles creating recorded showers exceeds 10^{14} ev. when $\rho\sim100$ particles/m^2. The evaluation of the number of particles in these showers gives a value

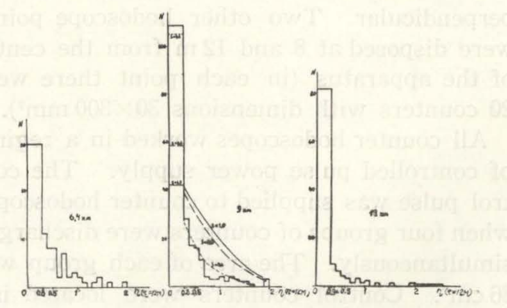

Fig. 2. The η-distribution of the "Vertical" showers. The smooth curves are derived on the assumption that lateral distribution of electrons in showers is described by the Nishimura-Kamata function. s- the age parameter.

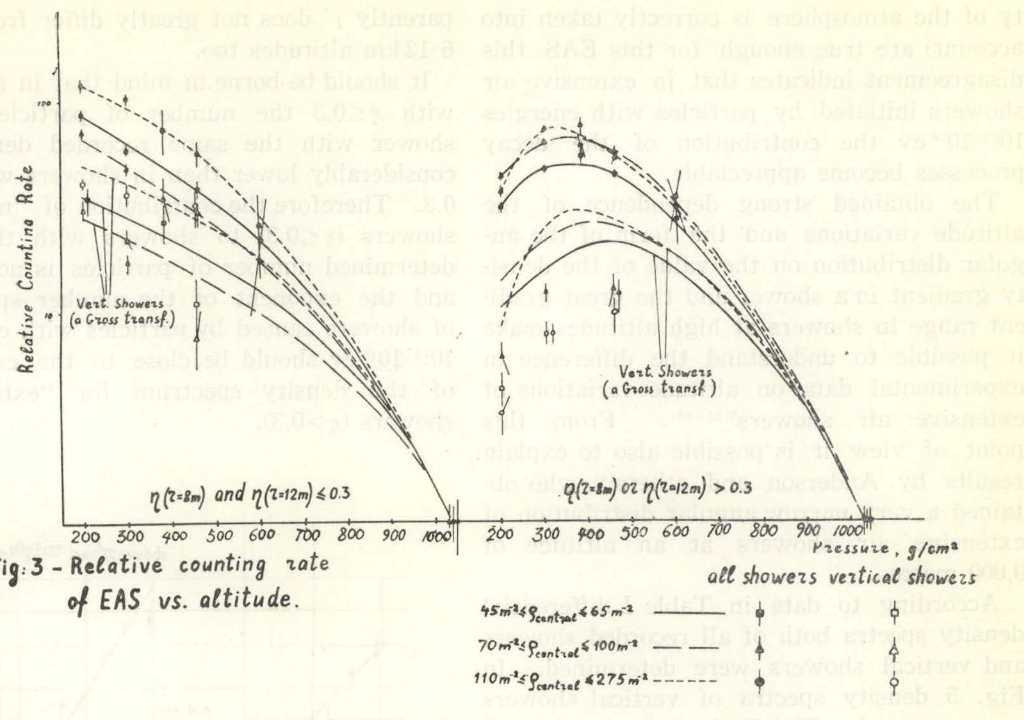

Fig. 3.

$N \gtrsim 10^5$.

Fig. 2 shows the $\eta\,(r=12\,\text{m})$ distribution of "vertical" showers. The comparison of all experimental data with corresponding calculation confirms the existence of "young" showers with narrow lateral distribution of particles at high altitudes.

Fig. 3 shows: (1) altitude variations of all recorded showers for three density groups (ρ_{central}), (2) altitude variations of vertical showers calculated from them by means of Gross's transformation[2)3)] and (3) data on vertical showers intensities obtained from the experiment.

Angular distribution of recorded showers may be determined by means of Gross's transformation. The m/n ratio distributions of showers were calculated from these angular distributions.

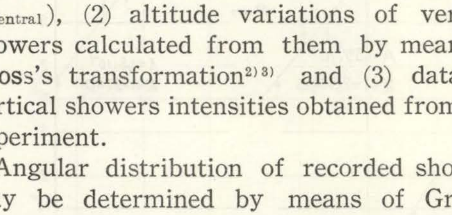

Fig. 4.

In Fig. 4 the m/n ratio distributions calculated for the mean-square scattering angle 10^0 and 30^0 are compared with experimental ones. The data refer to the showers in which 26–37 "horizontal" counters discharged. Data referring to the showers in which 15–26 "horizontal" counters were discharged and data referring to an altitude of 6.4 km are similar.

From data given it is evident that for showers with $\eta \leq 0.3$ systematic deviations of experimental values from those obtained by Gross's transformation are absent both in altitude variations and angular distributions. This shows that, on the one hand, the development of showers initiated by the particles with energies 10^{12}–10^{14} ev is determined by the thickness of matter the cascade passed. On the other hand, the approximations used for Gross's generalized transformation in this case are of sufficient accuracy.

The experimentally obtained altitude variations and angular distributions of showers with $\eta > 0.3$ systematically differ from values resulting from Gross's transformation. If the approximations used for Gross's transformation (in particular if the nonhomogenity of the atmosphere is correctly taken into account) are true enough for this EAS, this disagreement indicates that in extensive air showers initiated by particles with energies 10^{15}-10^{16} ev the contribution of the decay processes become appreciable.

The obtained strong dependence of the altitude variations and the form of the angular distribution on the value of the density gradient in a shower and the great gradient range in showers at high altitudes make it possible to understand the difference in experimental data on altitude variations of extensive air showers[3)8)-13)]. From this point of view it is possible also to explain results by Anderson and others[14)] who obtained a very narrow angular distribution of extensive air showers at an altitude of 9,000 metres.

According to data in Table I differential density spectra both of all recorded showers and vertical showers were determined. In Fig. 5 density spectra of vertical showers are presented. Fig. 5 also gives values A and $\gamma+1$ obtained by the least-square method for the approximation of spectra in the form $dH/d\rho = A\cdot(\rho/100\text{m}^{-2})^{-(\gamma+1)}$. Similar data on spectra of all recorded showers are listed in Table II.

Table II

Altitude	$A \frac{\text{Showers}}{\text{hour}\cdot\text{particles/m}^2}$		$\gamma+1$	
	$\eta\leq0.3$	$\eta>0.3$	$\eta\leq0.3$	$\eta<0.3$
Sea level	$5.6\cdot10^{-3}$	$1.4\cdot10^{-2}$	2.5 ± 0.7	2.65 ± 0.4
6.4 km	2.10^{-1}	$7\cdot10^{-1}$	2.5 ± 0.35	2.6 ± 0.2
9 km	$3.5\cdot10^{-1}$	$7.8\cdot10^{-1}$	2.4 ± 0.17	2.4 ± 0.1
12 km	$4.8\cdot10^{-1}$	$5.1\cdot10^{-1}$	2.6 ± 0.2	2.5 ± 0.2

Between exponent γ' of the number of particles spectrum and exponent γ of the density spectrum there is a difference depending on the rate of change of the average age parameter with the change of the number of electrons in showers. This difference depends on the mode of shower development. The evaluation made by Greisen for lower atmosphere has shown that $\gamma'-\gamma\cong0.02$[15)]. Experimental data obtained at sea level[16)] indicate that this estimate was true. Apparently γ' does not greatly differ from γ at 6-12 km altitudes too.

It should be borne in mind that in showers with $\eta\leq0.3$ the number of particles in a shower with the same recorded density is considerably lower than in showers with $\eta>0.3$. Therefore the contribution of "narrow" showers ($\eta\leq0.3$) to showers with the predetermined number of particles is not great and the exponent of the number spectrum of showers caused by particles with energies 10^{15}-10^{16} ev should be close to the exponent of the density spectrum for "extensive" showers ($\eta>0.3$).

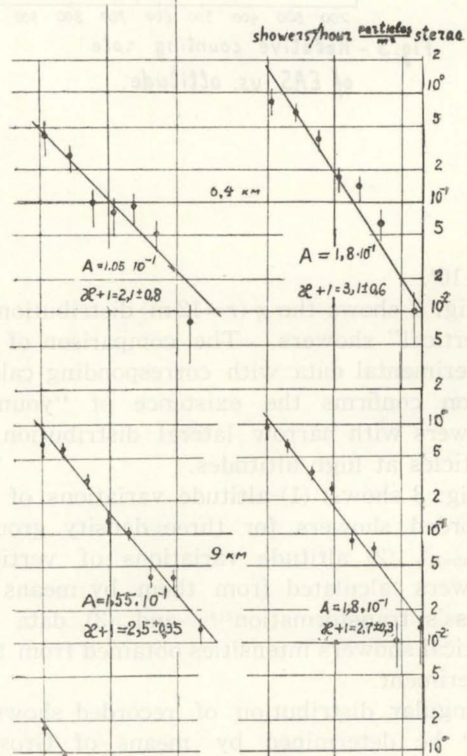

Fig. 5. The density spectra of the "vertical" showers.

Value γ' at high altitudes strongly depends on the model of development of extensive air showers.

Grigorov and Shestoperov gave calculations[17] for a case when the bulk of recorded showers is produced as a result of interactions of particles in which almost all the energy of interacting particles is conveyed to one gamma-ray quantum. According to these calculations at the altitudes of 9-12 km showers with the total number of particles 10^5-10^6 should have $3.5<\gamma'+1<4.5$. Data obtained on density spectra at altitudes of 9-12 km make it possible to conclude that in interaction of particles with energies 10^{15}-10^{16} ev with air nuclei in a considerable number of cases the imparting of almost all energy to the small number of π^0-mesons cannot take place.

The existence of vertical extensive showers at high altitudes and the shape of their spectra do not indicate any way that the energy conveyed to the electron-photon component considerably decreases with the increase of the interacting particle energy[18].

It should be noted that the maximum of the altitude curve of vertical showers is not shifted into the depth of the atmosphere with the increase of the shower size. Qualitatively this is in favour of the supposition that the energy of generated gamma-quanta does not essentially grow with the increase of the particles energies.

In order to render the above-mentioned conclusions quantitativly more definite corresponding calculations are intended.

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Discussion

Kamata, K.: I appreciate the results presented by Dr. Smorodin, and I don't think there is any substantial disagreement between Dr. Smorodin's data and ours. But I would like to make a brief remarks. First, we can not rule out the possibility that the classification due to η parameter in your experiment does not depend upon the difference of energy, but upon the distance from the core.

Second remark is on the density distribution. The interpretation of density distribution at high altitude should be very careful, and before reaching any definite conclusion we should keep in mind that there are many unknown parameters which might change the conclusion.

Smorodin, Yu. A.: The classification into narrow and extensive showers is only the qualitative one. Therefore, detailed analysis should be made, taking into account the shower size as well as the s-parameter. Sofar, the experimental results do not seem to have any discrepancy between Kamata's and ours.

Zatsepin, G. T.: For the upper layers of atmosphere where the density of air changes very quickly the Gross transformation cannot give very precise results. It seems quite natural, therefore, that the experimental data do not agree with the Gross transformations.

Smorodin: I agree with Dr. Zatsepin's remark on the accuracy of Gross transformation for high altitudes. I think that the difference observed in angular distribution must be understood only as an indication of the possibility of the effects associated with the decay process. It is possible that another indication of it is the result obtained by Clark *et al.* at mountain altitudes.