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III-4-10. On the Altitude Variation of Extensive Air Showers in the Upper Half of the Atmosphere

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The behavior of extensive air showers are investigated in the upper half of atmosphere. The zenith angle distribution of air showers with particle density more than $20\,\mathrm{m}^{-2}$ is observed by Fukui-Miyamoto discharge chamber at 8500 m above sea level. The observed result agrees with the altitude variation of shower intensity, and shows that the intensity maximum of vertical air shower is at the depth of 500–550 g cm^{-2} of air.

The lateral distribution of shower particles is measured by scintillator arrays at 7000 m above sea level. The average behavior of lateral distribution of the shower of size around 10^5 at this altitude observed within the distance of 0.1 Moliere unit from the core is approximately given by $f(r) \sim r^{-n}$; r in Moliere unit with, on the average, $n \sim 1.3$, but n of each shower fluctuates between 1.0 and 1.5.

The intensity variation with altitude of air shower is calculated using the shower curve theoretically obtained by Ueda and Ogita, and compared with experiment.

§1. Introduction

For understanding the development of extensive air showers, it is very important to get the knowledge on the behavior of air showers in the upper half of the atmosphere. However, at present one often meets the difficulty of understanding it because of the scarcity of experimental data at high altitudes. Then, the authors made the observations at airplane altitudes to get more experimental evidences on air showers. This experiment is now still being continued, and here we would like to present the data obtained so far.

§2. Altitude Variation of Shower Intensity

In earlier period of our experiment, the intensity variation with altitude of air showers was measured from sea level up to 6400 m using the simple threefold coincidence arrangement of Geiger counters[1]. The experimental arrangement is shown in Fig. 1. The six independent sets of this triangle arrangement were operated at a time. The average density of particles recorded in this experiment is $45\,\mathrm{m}^{-2}$ and $180\,\mathrm{m}^{-2}$, respectively. The observed result is shown in Fig. 1. The counting rate shows the exponential decrease

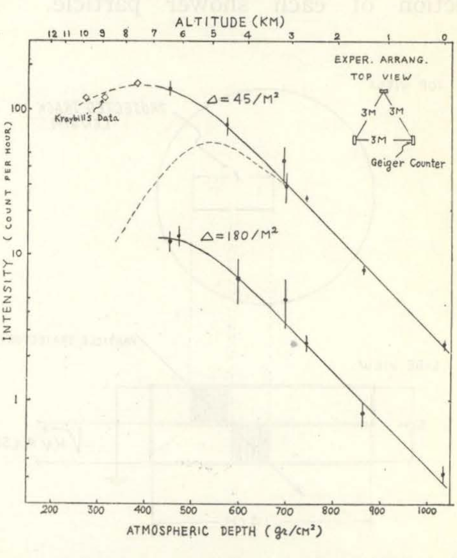

Fig. 1. Intensity variation with altitude of airshowers.

with atmospheric depth in the lower half of the atmosphere, and the absorption mean free path is $120 \pm 4\,g/cm^2$ of air for $45\,m^{-2}$, and $136 \pm 10\,g/cm^2$ for $180\,m^{-2}$, respectively. The observed intensity variation is extraporated using the data obtained by Kraybill[2] to higher altitudes. The intensity shown here is the omnidirectional intensity to which the showers from all directions contribute. From this curve, the vertical intensity curve is derived using the well known procedure of Gross transformation, and is shown by dashed line in Fig. 1.

§ 3. Zenith Angle Distribution at 8500 m

Another means of checking the vertical intensity is the zenith angle distribution of the intensity of air shower. Adams, Anderson and Cowan[3] observed the zenith angle distribution by cloud chamber at an altitude of 9500 m, but their result strongly contradicts with the vertical intensity curve mentioned above. This discrepancy thereafter has been supposed to indicate the possibility that the Gross transformation might be completely inapplicable at this altitude. In order to study this problem, the authors conducted the next experiment to observe the zenith angle distribution of air showers.

The experimental apparatus consists of scintillation counters and FM chamber. The FM chamber (Fukui - Miyamoto discharge chamber[4)5)]) is used to measure the incident direction of each shower particle. The chamber is made of glass in double decker fashion as is shown in Fig. 2. The high voltage pulse applied to the chamber is triggered by the threefold coincidence of scintillation counters (25 cm×25 cm×5 cm, each). As is illustrated in Fig. 2, the gaseous discharges develop between electrodes by the passage of charged particles, and then the projection of the line of these discharge columns gives the space angle of the incident direction of particles. These lines of discharge columns are photographed from the upper side. The experimental arrangement is shown in Fig. 3. The whole apparatus are mounted in the pressurized cabin of DC-8 jet plane[6)], and the observation was made at 8500 m above sea level. From the pictures obtained during the flight, such pictures are selected that shows at least two parallel tracks in the chamber to eliminate the contribution of badly scattered single particle. The zenith angle of incident direction of each shower particle is measured from these pictures, and the zenith angle distribution is obtained as is shown in Fig. 3 in which the intensities of the shower with particle density of about $20\,m^{-2}$ in the interval of 10 degrees are shown. The scale of ordinate is

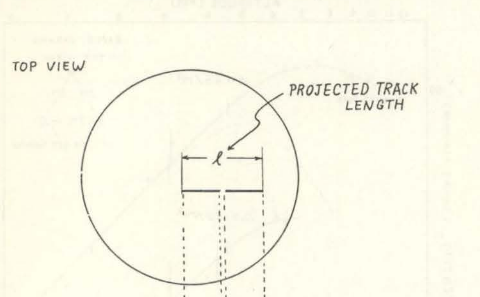

Fig. 2. Schematic Illustration of F. M. Discharge chamber.

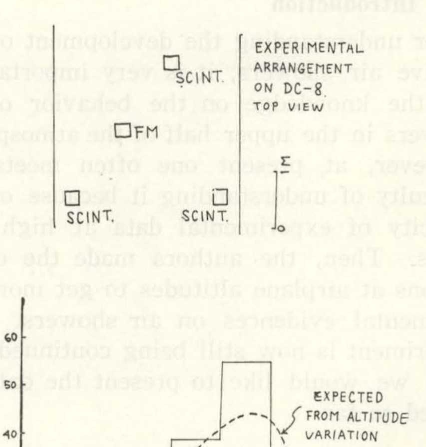

Fig. 3. Zenith angle distribution of air showers at 8500m observed by F. M. chambes.

not the intensity per unit solid angle, but the intensity per unit solid angle multiplied by sin θ, where θ is zenith angle. For comparison, the zenith angle distribution deduced from the vertical intensity curve shown in Fig. 1 is shown by dashed line in the same scale, where the total intensity is normalized to the observed intensity. As seen from this figure the observed distribution is in good agreement with the vertical intensity curve.

This result shows that the intensity maximum of vertical air showers with particle density of about several tens per square meter is at the atmospheric depth of about 500–550 g/cm^2. Furthermore, this result indicates that the Gross transformation can be applied to air shower phenomena still at this altitude without causing a serious error, and the physical assumptions underlying the Gross transformation roughly hold true at least at the lower two thirds of the atmosphere.

§4. Lateral Distribution at 7000 m

The next experiment was performed at 7000 m above sea level to observe the lateral distribution of shower particles by scintillator array. The experimental arrangement of scintillators installed in the cabin of DC-7C plane is shown in Fig. 4. The pulse

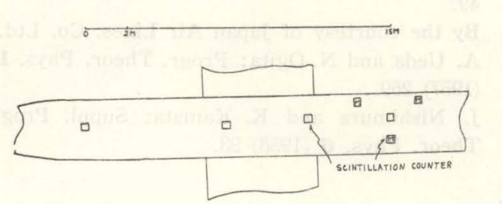

Fig. 4. Experimental arrangement on DC-7C. Flight altitude is 7000 m.

height of each scintillator is displayed on the cathode ray tube through the transisterized logarithmic amplifier, and is recorded by camera. The size of each scintillator is 25 cm×25 cm×5 cm. The master pulse is given by the threefold coincidence of three scintillators marked "M" in Fig. 4, and is actuated by the incidence of shower with particle density of about 20 m^{-2}.

The number of particles at the location of each counter is estimated from the pulse height record, and the lateral distribution is estimated for each individual shower. As our arrangement is "eccentric" arrangement, and the maximum available distance is 15 m, which is roughly equal to 0.1 Moliere unit at this altitude, the number of cases in which the lateral distribution can be decided is limited, and only 10 showers have been analyzed so far. Accordingly, as the statistical

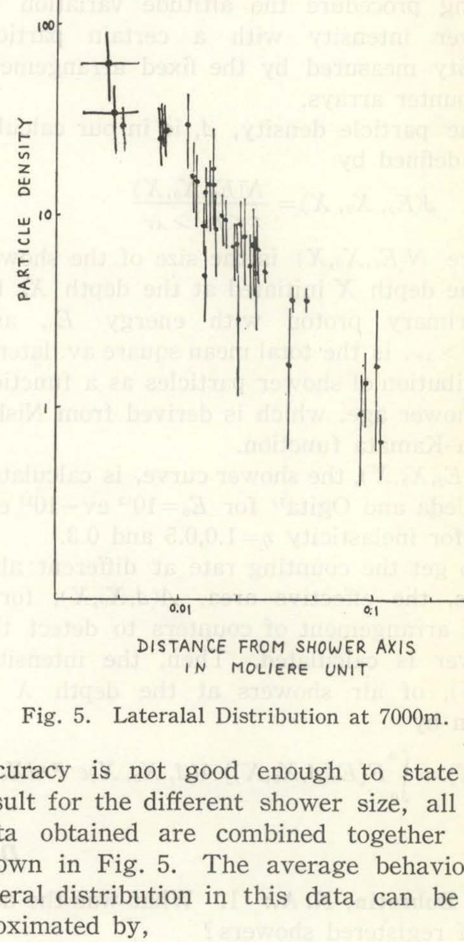

Fig. 5. Lateralal Distribution at 7000m.

accuracy is not good enough to state the result for the different shower size, all the data obtained are combined together and shown in Fig. 5. The average behavior of lateral distribution in this data can be approximated by,

$$f(r) \propto r^{-n},$$

where r is the distance from the core measured in Moliere unit. On the average, $n \sim 1.3$, but n of each individual shower shows large fluctuation, between 1.5 and 1.0. The distribution of size of these showers ranges from 10^4 to 10^6 with maximum contribution being from about 10^5. The age of the shower of size around 10^5 estimated from the observed lateral distribution at the depth of 420 g cm^{-2} is on the average 0.8–0.9, but each shower age fluctuates between about 0.6 and about 1.1.

§ 5. Calculation of Shower Intensity

In connection with the observation, a calculation was carried out to get the intensity variation with altitudes. The purpose of this calculation is to get the dependence of parameters of elementary interaction upon the observed intensity variation. To compare with the experiment, we derived by the following procedure the altitude variation of shower intensity with a certain particle density measured by the fixed arrangement of counter arrays.

The particle density, Δ, is in our calculation defined by

$$\Delta(E_0, X_0, X) = \frac{N(E_0,X_0,X)}{\pi < r_T^2 >_{AV}}$$

where $N(E_0,X_0,X)$ is the size of the shower at the depth X initiated at the depth X_0 by a primary proton with energy E_0, and $< r_T^2 >_{AV}$. is the total mean square av. lateral distribution of shower particles as a function of shower age, which is derived from Nishimura-Kamata function.

$N(E_0,X_0,X)$, the shower curve, is calculated by Ueda and Ogita[7] for $E_0 = 10^{13}$ ev-10^{17} ev, and for inelasticity $\eta = 1.0, 0.5$ and 0.3.

To get the counting rate at different altitudes, the effective area, $A(\Delta,X_0,X)$, for a fixed arrangement of counters to detect the shower is calculated. Then, the intensity, $f_\Delta(X)$, of air showers at the depth X is given by

$$f_\Delta(X) = \int_0^x F\{E_0(\Delta,X_0,X)\} A(\Delta, X_0, X) e^{-X_0} dX_0 \,.$$

where $F(E_0)$ is the energy spectrum of primary cosmic rays. In this calculation, the effect of variation of air density with altitude[8] is taken into account. The contribution of heavy primary is not considered.

The numerical integration is carried out for vertical shower with particle density of $45\,\mathrm{m}^{-2}$ and $180\,\mathrm{m}^{-2}$, and the result is compared with the experimental result which is shown in Fig. 1. One of the conclusion obtained in this comparison is that if the primary energy spectrum is approximated by a single power law with an exponent -1.8 in the integral spectrum, the experimental result fits to the assumption that $\eta \sim 1.0$. However, assuming that the primary spectrum has a knee at about 10^{15} ev, and that the value of exponent varies from -1.8 to -2.3 at this energy, the experimental result seems to fit better to the hypothesis that $\eta = 0.5 \sim 0.7$.

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Discussion

Dobrotin, N. A.: 1. What was the accuracy of the measurements of arriving angles of registered showers?

2. Have you compared the zenith angle distribution obtained in your experiments with the mountain data?

Kamata, K.: 1. 10 degrees.

2. I believe it is already established that the angular distribution at mountain altitude agrees with the distribution derived from altitude variation.