# *THE ENERGY SPECTRUM AND TOTAL NUMBER OF X-RAY PHOTONS IN EXTENSIVE COSMIC-RAY AIR SHOWERS*

G. A. BAZILEVSKAYA, A. F. KRASOTKIN, and A. N. CHARAKHCH'YAN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor October 11, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **46**, 1556-1560 (May, 1964)

Results of a study of low energy (x-ray) photons in extensive air showers are presented. The energy spectrum measured and the total number of x-ray photons in the showers are in agreement with the results of calculations for an equilibrium spectrum of photons produced in electron-photon cascades.

## INTRODUCTION

THE results of calculations of the equilibrium spectrum of low-energy photons (x-ray photons) produced in electron-photon cascades generated by primary electrons or photons of relatively high energies were reported earlier[1]. The calculations were made for air using the exact form of the well known Klein-Nishina and Tamm formulas for the Compton scattering of photons.

The comparison of the results of the calculations with the experimental data obtained with instrument counters mounted on pilot balloons[1] has shown that the intensity of the x-ray photons in the stratosphere is several times larger than the calculated value, whereas for photons with energies of several MeV there is a good agreement.

Recent papers[2,3] have reported measurements of x-ray photons of cosmic rays in the stratosphere. By analyzing the curve of the altitude dependence of the intensity of the photons in the stratosphere, the authors of these papers reached the conclusion that the intensity of the x-ray photons in the stratosphere can be attributed almost entirely to electromagnetic cascades, and it is difficult to assume, from energy considerations, that these photons are generated as a result of nuclear reactions of the neutrons in the stratosphere. It must be noted, however, that the altitude dependences of the electron, photon, and star-producing components (principally neutrons) of cosmic rays in the stratosphere do not differ strongly from each other. Therefore Jones[4], also using high altitude measurements of photons, arrives at a different conclusion—the x-ray photons in the stratosphere are due essentially to the star-producing component. Thus, so far it is impossible to explain satisfactorily the discrepancies between the experimental and calculated data for x-ray photons of cosmic rays in the stratosphere.

The conclusions drawn from the calculated numbers of x-ray photons in cosmic rays by means of the cascade theory are best verified, in our opinion, by experiments on extensive air showers (EAS), since the overwhelming majority of particles registered in the EAS are electrons and photons. To this end we measured the x-ray photons in the EAS, since there are still no published data on this subject. In addition, a comparison of the data on the energy spectrum of x-ray photons, obtained by measurements in EAS and in the stratosphere, is also of certain interest.

## APPARATUS

The measurements were made with two arrays Array I registered the number of triple coincidences in scintillation counters; array II measured the four-fold coincidences for three gas-discharge and one scintillation counter. NaI(Tl) cylindrical scintillators were used, one $40\times40$ mm in conjunction with an FÉU-42 photomultiplier, and one $70\times40$ mm with an FÉU-24 photomultiplier. The scintillator lining was 0.27 g/cm$^2$ aluminum. The measurements were carried out under a canvas cover.

The photomultiplier outputs were connected to voltage dividers, which set the thresholds for the registration of the pulses corresponding to the values of the energy released in the scintillator $E_{thr} \geq 34$, 50, 100, 170, 500, 1,000, and 2800 keV. The scintillation counters were calibrated with the aid of $Co^{60}$, $Cs^{137}$, and $Hg^{203}$. The pulses from the voltage divider at the output of the amplifier and from the shaping stages were fed to a Rossi triple-coincidence circuit. The resolution time of the electronic circuitry was $10^{-10}$ sec, making it possible to neglect the number of random coincidences.

The gas-discharge counters used in array II were of the MS-9 type, with 86 $cm^2$ area and glass walls 0.27 $g/cm^2$ thick. The counters were connected in parallel, 15 in each tray. The thickness of the tray walls was 0.27 $g/cm^2$ of aluminum.

## MEASUREMENTS

Array I was used to measure the number of triple coincidences in scintillators located in a horizontal plane at the vertices of an equilateral triangle as a function of the distance between the scintillators. The results of these measurements are shown in Fig. 1. The statistical errors for these data are smaller than 5%. The abscissas show the distance between the centers of the counters. In both cases $E_{thr} \geq 50$ keV, corresponding to $\sim 2 \times 10^{-3}$ of the energy released by the relativistic particle along its path to the crystal.

It is clear from Fig. 1 that for $R > 50$ cm the number of triple coincidences is practically independent of the distance. Choosing $R = 1$ meter, we assume that the triple coincidences which we registered are due to the EAS particles, mostly photons, as will be made clear later on. It is seen from Fig. 1 that the number of triple coincidences measured at mountain altitudes is practically 13 times the number at sea level, in agreement with the results of analogous measurements for the charged component of EAS. However, as will become clearer below, the number of triple coincidences measured with the aid of scintillation counters ($E_{thr} \geq 50$ keV), both in the measurements at Dolgoprudnyĭ and in the measurements on the Tyan'-Shan' high-mountain station of the Academy of Sciences Physics Institute, is approximately 15 times larger than the number of triple coincidences for the high-discharge counters with the same area. Thus, these data show that the photon component of the extensive air showers is in equilibrium with the electrons.

Figure 2 contains data on the number of triple coincidences in scintillation counters ($R = 1$ meter) as a function of $E_{thr}$ (the values of $E_{thr}$ were the same for all three scintillators). The ordinates are the ratios of the measured number of triple coincidences to the number of triple coincidences for the gas-discharge counters. It is seen from this figure that the bulk of the triple coincidences measured by the scintillators is actually due to the x-ray photons of the EAS.

## PHOTON DENSITY SPECTRUM

To investigate the energy spectrum of the x-ray photons in the EAS it is necessary to find the density spectrum of the registered photons. We used the method of variation of the areas of the scintillation counters, similar to what was done for the electrons in EAS.

Assuming a Poisson probability for the passage of the photon through a given area, just as in the case of the EAS electron, the number of triple coincidences $C_3$ in detectors with area $\sigma$, as is well known[5], is given by

$$C_3 = A \int_0^\infty (1 - e^{-\alpha\rho\sigma})^3 \rho^{-(\varkappa+1)} d\rho = Q(\varkappa) \, [\alpha\sigma]^{\varkappa},$$

where $\rho$ — particle density in the shower, $A\rho^{-(\kappa+1)}$ — differential spectrum of the densities ($\kappa$ — constant), $\alpha$ — efficiency with which the counter registers the radiation, Q — some function of $\kappa$ which does not depend on $\sigma$ (the detector area).

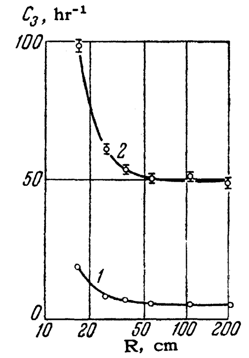


FIG. 1. Number of triple coincidences measured with the aid of scintillators as a function of the distance between them: 1 – results of measurements near sea level (city of Dolgoprudnyĭ), 2 – at altitude 3,330 meters (Tyan'-Shan').

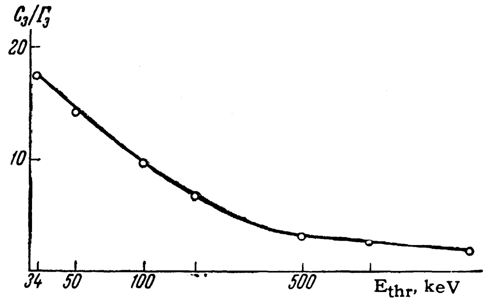


FIG. 2. Ratio of number $C_3$ of triple coincidences in scintillators to the number $\Gamma_3$ of triple coincidences in gas discharge counters having the same area as a function of the energy-release threshold.

For scintillation counters with low thresholds the efficiency of electron registration is practically 100%, and for photons this efficiency was denoted by $\mu$; then the total density of the particle flux registered by the scintillation counter is

$$\rho = \rho_{el} + \mu\rho_{ph}$$

where $\rho_{el}$ — electron density, $\rho_{ph}$ — photon density, and $\mu$ — efficiency for the registration of photons with energy larger than the specified value. Assuming that the number $N_p$ of shower photons with energy $> E$ is connected with the total number of cascade electrons $N_{el}$ by the linear relation $N_{el} = k(E)N_{ph}$, we can write $\rho_{el} = k\rho_{ph}$ and $\alpha = k + \mu$. It must be noted that in the case of scintillation counters the number $C_3$ for triple coincidences is only approximate, since it is valid if the photon registration efficiency does not depend on $\rho$. This dependence can be neglected actually only at very low energy-release thresholds, when the efficiency for the registration of photons by the scintillation counter is close to 100%, similar to the efficiency of registration of the electrons by the gas discharge counter.

By measuring the number of triple coincidences with the aid of scintillation counters of two sizes at the same value of $E_{thr}$ we obtain the values of the index of the photon-component density spectrum:

$$\varkappa = \log\frac{C_3(\sigma_1)}{C_3(\sigma_2)} \Big/ \log\frac{\sigma_1(\mu_1 + k)}{\sigma_2(\mu_2 + k)}.$$

The ratio $\sigma_1(\mu_1 + k)/\sigma_2(\mu_2 + k)$ of the effective areas of the scintillators was calculated from the geometrical dimensions of the counters assuming isotropic distribution of the photons in the upper hemisphere and assuming that $\mu_1 = \mu_2$. The values obtained for $\kappa$ at low $E_{thr}$ in mountain-altitude measurements are

| | | | |
|---|---|---|---|
| $E_{thr}$, keV = | 34 | 50 | 100 |
| $\varkappa =$ | $1.55 \pm 0.09$ | $1.52 \pm 0.03$ | $1.55 \pm 0.07$ |

For electrons $\kappa = 1.5$. It is seen from these data that $\kappa$ depends little on the chosen thresholds and coincides with the value of $\kappa$ for the electrons (in identical density intervals).

## PHOTON ENERGY SPECTRUM

Investigations of the energy spectrum of the photons were made with the aid of two arrays. In the first, as already mentioned, the number of triple coincidences $C_3(\sigma, E \geq E_{thr})$ was measured as a function of $E_{thr}$. In this case, according to [5], one can write approximately for the number $C_3(\sigma, E \geq E_{thr})$ divided by the number of triple $\Gamma_3(\sigma)$ of the triple coincidences measured with the gas-discharge counters

$$C_3(\sigma, E \geqslant E_{thr}) / \Gamma_3(\sigma) \cong (1 + \mu/k)^{\varkappa}.$$

In the second array we measured four-fold coincidences in three gas-discharge counters with area S and one scintillation counter with area $\sigma$. If $S \gg \sigma$ we can write

$$C_4(\sigma, E \geqslant E_{thr}) / \Gamma_4(\sigma) \cong 1 + \mu/k,$$

where $\kappa = 1.5$; k — ratio of the density of the electrons to the density of the photons, which depends on $E_{thr}$; $\mu$ — probability of energy release in the crystal $E \gg E_{thr}$ by a photon of energy $\epsilon \geq E$. It is convenient to use for the description of the energy spectrum of the photons in EAS the dependence of $\mu/k$ on $E_{thr}$, which can be directly set in correspondence with the analogous dependence obtained in measurements of single photons in the stratosphere. The reason why the formulas for $C_3$ and $C_4$ are approximate is that the dependence of $\mu$ on the photon density is neglected. However, for $C_4$ this neglect is of lesser importance.

Figure 3 shows the dependence of $\mu/k$ on $E_{thr}$, obtained from data in the stratosphere (dashed line) and in EAS. It is seen from this figure that the energy spectrum of the x-ray photons in the EAS is satisfactorily described with the aid of the results of the calculations obtained earlier [1]. The difference between the data obtained in the measurements with array I, as already noted, is more likely to be connected with the inaccuracy in the formula for $C_3$. Thus, the data of the calculations of the equilibrium spectrum of the x-ray

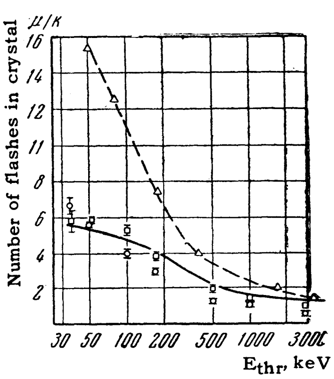


FIG. 3. Ratio of number of flashes produced by photons in the scintillator to the number of flashes produced by the electrons ($\mu$/k) as a function of the energy release threshold $E_{thr}$: Δ – data of stratosphere measurements. The EAS measurement data are as follows: o – with three scintillation counters, □ – with three gas-discharge counters and one scintillation counter; continuous line – result of calculation[1].

photons, produced in electron-photon cascades, are in good agreement with experiment for EAS. The intensity of the x-ray photons registered in the stratosphere can apparently not be attributed to the cascade processes alone.

[1] A. N. Charakhch'yan and T. N. Charakhch'yan, JETP **40**, 1602 (1961), Soviet Phys. JETP **13**, 1126 (1961).

[2] J. I. Vette, J. Geophys. Res. **67**, 1731 (1962).

[3] L. E. Peterson, J. Geophys. Res. **68**, 979 (1963).

[4] F. C. Jones, J. Geophys. Res. **66**, 2029 (1961).

[5] G. T. Zatsepin, Candidate's Dissertation, Phys. Inst. Acad. Sci. 1950.

Translated by J. G. Adashko
233