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ENERGY SPECTRUM AND TOTAL NUMBER OF LOW-ENERGY COSMIC-RAY PHOTONS IN THE STRATOSPHERE

A. N. CHARAKHCH'YAN and T. N. CHARAKHCH'YAN

P. N. Lebedev Physics Institute, Academy of Sciences U.S.S.R.; Institute of Nuclear Physics, Moscow State University

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Results of calculations and experiments on the energy spectrum of cosmic-ray photons in the stratosphere (in the energy range from 50 to 3000 kev) are presented.

It is customarily assumed that the main source of low-energy photons (tens of kev and more) in the cosmic rays of the stratosphere is electron bremsstrahlung. It is of interest to verify this premise by calculation and experiment. We propose that the following calculations indicate that this assumption is not justified for the softest part of the spectrum of the stratosphere photons.

At not too high altitudes in the stratosphere, owing to electromagnetic cascade multiplication, the energy spectrum of the electrons or photons is the average of a large number of superimposed cascades from different generations. The photon spectrum in the stratosphere will therefore be close in form to the equilibrium spectrum (integrated over the depth) obtained in the theory of cascade showers.[1] In addition, the energy spectrum for the photons of energy many times smaller than the energy of the electrons or photons which give rise to avalanches, will be independent of the initial energy of the photons and the electrons. As shown by us earlier,[2] such a theoretical interpretation is well justified experimentally when it comes to the low-energy electrons in the stratosphere.

Belen'kii[1] gives for the equilibrium spectrum of the photons the following integral equation

$$\int_E^\infty P(E')\,W_e(E'E)\,dE' - \sigma(E)\,\Gamma(E) + \int_E^\infty \Gamma(E')\,W_k(E'E)\,dE' = 0, \tag{1}$$

where $\Gamma(E)$ is the sought photon distribution function, $P(E')$ is the electron distribution function,

$$\sigma(E) = \int_0^E [W_p(EE') + W_k(EE')]\,dE'$$

is the total photon absorption cross section along a unit cascade path, and W_e, W_p, and W_k are the cross sections on a cascade unit path of the electron bremsstrahlung, pair production by photons, and Compton scattering of photons, respectively.

The first term of Eq. (1) is the number of bremsstrahlung photons of energy E generated on a unit path. As a good approximation, $W_e(E'E) = A/E$ (case of total screening), and

$$\int_E^\infty P(E')\,dE' = N(E)$$

is the equilibrium electron integral spectrum, the expression for which was given in reference 1. The second term of the equation is the number of photons of energy E absorbed on a unit path. The third term of the equation takes into account photons with energy E, obtained by Compton scattering from photons with energy $E' > E$.

The complexity of the expression for W_k in (1) makes it difficult to solve the equation in general form. Solutions were obtained for the simplified formulas $W_k = g/E'E$ (Belen'kii[1]) and $W_k = (g/E'E)\,[1 + (E/E')^2]$ (Isaev[3]). The exact expression for W_k in (1), given by the well known Klein-Nishina and Tamm formula, has the form

$$W_k(E'E) = \frac{g}{E'E}\left[1 + \left(\frac{E}{E'}\right)^2 - \frac{2mc^2}{E'^2}(E' - E) + \frac{(mc^2)^2}{E'^3}\frac{(E - E)^2}{E}\right]. \tag{2}$$

Here E′ and E are the energies of the primary and secondary photons, in Mev, mc^2 is the electron rest-mass energy, and $g = 1.32$ Mev.

The foregoing approximations are not good enough for photons with energies less than 4 — 5 Mev. We have attempted to obtain a solution of (1) by using the exact expression for $W_k(E'E)$ in (2).

Let us introduce

$$\Gamma(E) = \frac{N(E)}{E}\,\frac{Z(E)}{\sigma(E)}. \tag{3}$$

After substituting $\Gamma(E)$ in (1) we obtain for $Z(E)$ the expression

$$A - Z(E) + \frac{E}{N(E)} \int_{E}^{E_1} \frac{W_k(E'E)}{E'\sigma(E')} N(E') Z(E') dE' = 0. \quad (4)$$

Unlike the methods of references 1 and 3, in which the photons involved have relatively high energies, the upper limit of the integral in (4) is in general not infinite, for E_1 becomes infinite only when $E \geq 0.25$ Mev. For smaller values of E, the upper limit of E_1 is determined from the well known relation $E = mc^2E_1/(mc^2 + 2E_1)$, obtained from the energy and momentum conservation laws in the Compton scattering of photons.

The solution of (4) is sought in the form of a series in powers of $\mu \leq 1$, a parameter introduced as a factor in the third term of (4):

$$Z(E) = \sum^{\infty} \mu^n Z_n(E). \quad (5)$$

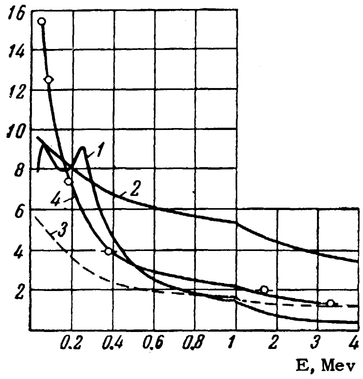
Naturally, such a solution will correspond to our problem when $\mu = 1$. Substituting the series (5) into (4) and equating the terms of like powers of μ to zero, we obtain the terms of the series

$$Z_0 = A, \quad Z_1 = \frac{E}{N(E)} \int_{E}^{E_1} \frac{W_k(E'E)}{E'\sigma(E')} N(E') Z_0(E') dE',$$
$$Z_2 = \frac{E}{N(E)} \int_{E}^{E_1} \frac{W_k(E'E)}{E'\sigma(E')} N(E') Z_1(E') dE', \ldots \quad (6)$$

For sufficiently small values of E we have $A = 1.3$ (see reference 1).

In view of the complexity of the integrand, the integrals were evaluated numerically. The series (5) converges rather rapidly also when $\mu = 1$. The remainder of the series amounts to not more than 1% of the sum of the first five or six terms. For low energies, from 0.02 to 0.1 Mev, the values of $\delta(E)$ in (3) and (6) were taken with account of the photoabsorption effect. The calculated differential spectrum of the photons is shown for the case of air in the figure, curve 1. The ordinates show the ratio of the number of photons with energy E in a 1-Mev interval to the total number of equilibrium electrons, $N_e = E_0/\beta$, and the abscissas represent the photon energy. Curve 2 is for the integral spectrum.

The experimental data on the intensity of low-energy photons in the stratosphere have been obtained by measurements with the aid of a scintillation counter. The apparatus consisted of a cylindrical 40 × 40 mm NaI(Tl) scintillator with FÉU-1S photomultiplier. Connected to the output of the photomultiplier was a two-stage amplifier and the electronic portion of the circuit, used to broadcast the number of flashes in the scintillator.



Curve 1 – differential spectrum of photons in air: ordinates – ratio of equilibrium number of photons with energy E in a 1-Mev interval to the total number of cascade electrons; abscissas – photon energy E; 2 – corresponding integral spectrum of the photons; 3 – calculated ratio of the frequency of flashes in the crystal to the total number of electrons, as a function of E_{thr}; 4 – experimental ratio of frequency of flashes in the crystal to the total number of electrons, as a function of E_{thr}.

A voltage divider was inserted between the output of the photomultiplier and the amplifier in order to set the threshold for the registration of a specified pulse amplitude, corresponding to an energy release in the crystal, Ethr, greater than 50, 85, 170, 480, 1700, and 3200 kev. The measurements have been carried out at geomagnetic latitude 51° and altitudes up to 33 — 35 km. The results of the experiment, pertaining to the altitude at which the photons had maximum intensity (100 g-cm^{-2}) are shown dotted in the figure. The ordinates represent the ratio of the frequency of the scintillations in the crystal, after subtracting the scintillations corresponding to charged particles, to the total number of electrons at the same altitude. The abscissas represent the value of E_{thr} (to obtain the number of scintillations per second produced in the crystal by the photons, it is necessary to multiply the ordinates of curve 4 by 18).

The experimental data obtained are comparable with the expected integral spectrum of the recoil electrons in the crystal due to photons. The integral spectrum of the recoil electrons in the scintillator was determined by first calculating the equilibrium spectrum of the photons and using the data on the cross section of the absorption of the photons in the NaI(Tl) crystal as a function of their energy.[4] The results of these calculations are represented by curve 3. As can be seen from the figure, the total flux of registered photons is practically three times greater than expected. The discrepancy is less significant for photons with energies greater than several Mev. There is little likelihood that this disparity in the spectrum can be attributed to inaccuracy in the measurements. This inaccuracy is less than 10 or 15%, and the accuracy of the numerical calculations is approximately 10%.

It should be noted that the experimental data on the spectrum of the photons obtained at other altitudes, both before and after the maximum of the intensity curve, practically coincide with the data at the maximum. In addition, the ratio of the total number of registered photons to the total number of electrons also depends little on the altitude. These features of the altitude dependence speak in favor of a cascade origin of the low-energy photons in the stratosphere. It is difficult at present, however, to draw any final conclusion concerning the causes of disparity between the experimental and calculated data.

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[1]S. Z. Belen'kii, Лавинные процессы в космических лучах (Cascade Processes in Cosmic Rays), Gostekhizdat, 1948, pp. 79, 106, 20.

[2]A. N. Charakhch'yan and T. N. Charakhch'yan, JETP **35**, 1088 (1958), Soviet Phys. JETP **8**, 761 (1959).

[3]P. S. Isaev, JETP **24**, 78 (1953).

[4]Chechik, Faĭnshteĭn, and Lifshitz, Электронные умножители (Electron Multipliers), Gostekhizdat 1957, p. 514.

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274