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**Abstract**

**Full Text**

*Physics*

A. A. VARFOLOMEEV, D. I. GOLENKO, and I. A. SVETLOLOBOV

## CHARACTERISTICS OF ELECTROMAGNETIC CASCADES IN PHOTOGRAPHIC EMULSION WITH ALLOWANCE FOR THE INFLUENCE OF THE MEDIUM ON RADIATION PROCESSES

*(Presented by Academician I. V. Kurchatov, 29 V 1958)*

This paper gives the results of Monte Carlo calculations of electromagnetic cascades, over distances up to 1.5 radiation units, produced by electrons with initial energies of  $10^{11}$  and  $10^{12}$  eV. The calculations were carried out taking into account the actual, nonasymptotic cross sections of the elementary electromagnetic processes (as functions of the particle energy). Two variants of the calculations were performed. In one variant only the Bethe and Heitler relations for the elementary processes were used; in the other, in order to take into account the influence of the medium on the radiation processes of high-energy electrons, formulas from the work of A. B. Migdal <sup>(1)</sup> were used. The calculation conditions were chosen in accordance with the experimental features of the photographic-emulsion method. In setting up the problem, the following considerations were taken into account.

It is of interest to verify experimentally the presence of effects of the influence of the medium on the processes of bremsstrahlung at high energies of the radiating particles. According to the works <sup>(2,3)</sup>, the probability of emission of soft quanta by a high-energy electron should be smaller than that given by the results of the usual Bethe-Heitler theory, owing to the influence of multiple scattering of the electrons <sup>(2)</sup> and owing to polarization of the medium <sup>(3)</sup>. Detailed formulas taking both these effects into account were obtained by Migdal <sup>(1)</sup>. The effects should be manifested the more strongly, the higher the energy of the electron and the lower the energy of the emitted quantum.

**Fig. 1.** Differential energy spectrum of electron-positron pairs formed in photographic emulsion at depths  $t_1$  and  $t_2$ . The initial energy of the primary electron is  $E_0 = 10^{12}$  eV. 1 — calculation according to Bethe and Heitler; 2 — calculation taking into account Migdal's formulas.

The presence of these effects can in principle be checked from the energy spectra of electrons in high-energy electron-photon showers in cosmic rays. With the

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Figure 2

Figure 2: Figure 2

aid of large stacks of photographic-emulsion layers exposed at great altitudes, electron-photon showers with energies of  $10^{11}$ – $10^{12}$  eV are registered with sufficient efficiency over distances of several radiation lengths. In this case it is possible to reconstruct the spatial pattern of the shower with high accuracy and to measure the energy spectrum of secondary electrons (pairs) in the region  $10^6 \div 5 \cdot 10^9$  eV by multiple scattering. Estimates made show that, for

of detecting the effects under consideration with the experimental possibilities available, it makes sense to investigate electron-photon showers with an initial energy of  $10^{11} \div 10^{12}$  eV at the beginning of their development and at depths up to  $1 \div 1.5$  radiation lengths. Thus, it is desirable to have theoretically expected spectra of shower particles that are valid in the region of not very high energies of these particles and at small depths. The latter condition requires proper accounting for the cross sections of elementary processes. The use of asymptotic values of the cross sections, as is done in ordinary cascade theories, becomes invalid at such small depths for the energies of secondary particles under consideration. In addition, to account for the influence of the medium it is necessary to use correct values of the bremsstrahlung cross sections. This determines the choice of the Monte Carlo method of calculation.

**Fig. 2.** Differential energy spectrum of secondary electrons (positrons) reaching depths  $t_1$  and  $t_2$ , respectively. The initial energy of the primary electron is  $E_0 = 10^{12}$  eV. Histogram 1—calculation according to Bethe and Heitler; histogram 2—calculation taking into account Migdal' s formulas; curve 3—calculation by Arley.

To facilitate the task of detecting the effects considered, it was decided to carry out calculations, on the one hand, within the framework of the ordinary Bethe-Heitler theory (B.-H.) and, on the other hand, taking into account Migdal' s formulas (M.).

The conditions for calculating the cascades were as follows. The primary particles were taken to be electrons with energies  $10^{11}$  and  $10^{12}$  eV. All particles with total energy greater than  $1.5 \cdot 10^6$  eV were followed. The following elementary processes in the field of the nuclei and electrons of the emulsion components were

taken into account: bremsstrahlung, pair production by photons, pair production by electrons, the Compton effect, photoelectric absorption, and ionization braking of electrons. The cross sections of the elementary processes were calculated with allowance for the nuclear composition of Ilford G-5 emulsion. (The value  $t_0 = 2.90$  cm was adopted as the radiation unit of length.) The spatial distribution of particles was not taken into account. The problem was considered one-dimensional. The resulting data were referred to two values of the depth  $t$  (distance from the beginning of the primary electron path):  $t_1 = 1.0t_0$  and  $t_2 = 1.5t_0$ . All calculations were performed on an electronic computer. On average, for each of the two variants at one value of the primary energy, 100 trees were calculated.

As a result, for each of the variants the following data were obtained:

- 1) Energy spectra of electron-positron pairs formed at depths up to  $t_1$  and  $t_2$ , respectively, for an initial energy of  $10^{12}$  eV (Fig. 1) and  $10^{11}$  eV (Table 1).
- 2) Energy spectra of electrons reaching depths  $t_1$  and  $t_2$ , respectively, for an initial energy of  $10^{12}$  eV (Fig. 2) and  $10^{11}$  eV (Table 1).
- 3) Certain data that make it possible to judge the fluctuations of the results and the dependence of the fluctuations on the depth  $t$  under consideration, on the initial energy, and on the energy interval of the secondary particles.

As is seen from Fig. 1, at an initial energy  $E_0 = 10^{12}$  eV the number of pairs with energies  $\leq 10^9$  eV decreases, owing to the influence of the medium, by  $\sim 2.5$  times at a depth—

Table 1

Differential energy spectra of electrons and pairs in a shower produced by a primary electron with energy  $10^{11}$  eV

Energy interval, eV	Number of pairs, $t_1$ , B.-G.	Number of pairs, $t_1$ , M.	Number of pairs, $t_2$ , B.-G.	Number of pairs, $t_2$ , M.	Number of electrons, $t_1$ , B.-G.	Number of electrons, $t_1$ , M.	Number of electrons, $t_2$ , B.-G.	Number of electrons, $t_2$ , M.
$10^6 - 3 \cdot 10^6$	0.030	0.012	0.129	0.084	0.307	0.120	0.950	0.614
$3 \cdot 10^6 - 5 \cdot 10^6$	0.040	0.012	0.099	0.145	0.228	0.145	0.594	0.385

Energy in-ter-val, eV	Number of pairs, $t_1$ , B.-G.	Number of pairs, $t_1$ , M.	Number of pairs, $t_2$ , B.-G.	Number of pairs, $t_2$ , M.	Number of elec-trons, $t_1$ , B.-G.	Number of elec-trons, $t_1$ , M.	Number of elec-trons, $t_2$ , B.-G.	Number of elec-trons, $t_2$ , M.
$5 \cdot 10^6 - 10^7$	0.109	0.096	0.525	0.313	0.466	0.398	1.287	0.927
$10^7 - 3 \cdot 10^7$	0.416	0.313	1.238	1.048	0.930	0.771	2.742	2.180
$3 \cdot 10^7 - 10^8$	0.594	0.602	1.881	1.590	1.158	1.012	3.238	2.746
$10^8 - 3 \cdot 10^8$	0.594	0.422	1.871	1.301	1.020	1.00	2.881	2.277
$3 \cdot 10^8 - 10^9$	0.505	0.639	1.416	1.518	1.069	1.036	2.188	2.337
$10^9 - 3 \cdot 10^9$	0.643	0.446	1.198	1.024	0.792	0.807	1.456	1.903
$3 \cdot 10^9 - 10^{10}$	0.396	0.400	1.078	1.014	0.722	0.699	1.554	1.349
$10^{10} - 10^{11}$	0.545	0.518	0.991	0.939	1.129	1.156	1.198	1.120

depth  $t_1 = 1.0t_0$  and by almost a factor of 2 at the depth  $t_2 = 1.5t_0$ . For  $E_0 = 10^{11}$  eV (Table 1), the number of pairs with energies  $\leq 3 \cdot 10^8$  eV decreases by approximately 20%. The difference in the electron spectra is somewhat smaller. Hence it is clear that it is more advantageous to measure the spectra of electron-positron pairs.

In Fig. 3 are shown the distributions of trees according to the number of all electrons at energy  $E_0 = 10^{12}$  eV. It is seen that the relative fluctuations are larger when the influence of the medium (M.) is taken into account.

The results obtained show that the study of only a few showers with energy  $10^{12}$  eV already makes it possible to draw definite conclusions about the presence of the effects under consideration. For showers with energy  $10^{11}$  eV, several times more would be needed for the same purpose.

Although the calculations were carried out for a specific medium—photoemulsion—the results obtained can, with certain allowances, be used for other media. In any case, they will prove useful where it is not justified to use the asymptotic Bethe and Heitler formulas for elementary processes, as is done in all existing cascade theories. Among analytical calculation methods at small depths, the method of successive approximations is the most valid. In Fig. 2, for comparison, the differential electron spectrum obtained by us (in the form of histograms) and Arley's curve<sup>4</sup> for the same spectrum, obtained by the method of successive approximations, are shown. In the soft region a substantial difference is visible.

Fig. 3. Distribution of trees according to the number of all electrons with energy  $\geq 1.0 \cdot 10^6$  eV, reaching depth  $t_1$ . The initial energy of the primary electron is  $E_0 = 10^{12}$  eV. 1—calculation according to Bethe and Heitler; 2—calculation taking into account Migdal's formulas

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