INVESTIGATION OF ELECTRON-PHOTON SHOWERS WITH SCINTILLATION COUNTERS

O. A. ZAĬMIDOROGA, V. M. KUT'IN, Yu. D. PROKOSHKIN and V. M. TSUPKO-SITNIKOV

Joint Institute for Nuclear Research

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We have measured cascade curves, fluctuations in the number of secondary electrons, and angular divergence for showers produced in lead by 115 and 217 MeV electrons. The shower characteristics were determined by analysis of the pulse-height distributions of a scintillation counter used to measure the number of electrons in the shower. Measurements were made for various values of cutoff energy of the secondary electron spectrum.

1. INTRODUCTION

Most of the experimental information existing at the present time on electron-photon showers in materials with high Z was obtained by means of track devices—bubble chambers, spark chambers, and cloud chambers. Track devices provide the possibility of obtaining a directly usable and detailed picture of the development of the electromagnetic cascade, which is particularly important in the first stages of studying the cascade process. At the same time these visual methods have their deficiencies, the most important of which are the poor statistics and the great labor of analyzing the results.

The shower studies which have been made with other types of particle detectors—ionization chambers,[1] gas-discharge counters,[2] and Cerenkov counters,[3] although free from the difficulties mentioned above, have permitted the study only of the averaged characteristics—the cascade curves[2,3] and ionization loss[1] of showers. However, in order to solve many of the technical problems of experimental physics (determination of γ-ray and electron detector efficiency, energy resolution of total-absorption spectrometers, and so forth) it is necessary to know not only the averaged characteristics of showers but also the detailed probabilities—the fluctuations in the number of particles in the shower and the correlation of these fluctuations.

If a Cerenkov counter is used to study showers, the counter must have a considerable thickness in order to provide sufficient light yield. This limits the energy cutoff of the electron spectrum recorded in the shower to a value $E \gtrsim 10$ MeV.[3] Shower characteristics depend substantially on the value of E.[4] Thus, in a shower developed in lead, electrons with energy above $E \approx 1$ MeV carry about 50% of the energy of the entire shower,[5] and above E = 10 MeV still less—30%.[6] The average number of electrons at the maximum of the cascade curve decreases by 1.5 times as E changes from 1 to 10 MeV, and for greater thicknesses of absorbing material this change becomes even more important.[5] Many particle detectors used in high energy physics have a low threshold for electron detection (1 MeV or below). In order to determine the parameters of these devices as shower detectors it is necessary to have experimental information on the characteristics of electromagnetic showers for small values of E. The calculation of showers in this region is particularly difficult.

In the present work we used a scintillation counter spectrometer to measure the number of shower electrons at different depths of shower development. As a consequence of the small thickness of the scintillator (1 g/cm^2 of polystyrene) the counter could efficiently record shower electrons with a cutoff energy $E \approx 2$ MeV. The purpose of the work was to determine such shower characteristics as cascade curves, fluctuations in the number of particles, and angular divergence of the particles for different values of E. The experiments were performed in the electron beam of the synchrocyclotron of the Laboratory of Nuclear Problems, Joint Institute for Nuclear Research.[7,8]

2. EXPERIMENTAL ARRANGEMENT

The experimental setup is sketched in Fig. 1. A beam of γ rays from decay of π^0 mesons produced in proton bombardment of an internal target in the synchrocyclotron, struck a lead converter. The electrons produced as the result of γ-ray conversion were analyzed by a magnet. The electron beam was separated by scintillation counters C_1 (10 × 10 cm), C_2, and C_3 (3 × 3 cm), which were connected to a nanosecond coincidence circuit.[9] The electron beam then passed through lead and graphite absorbers and a scintillation counter spectrometer C_4 (12 × 12 × 1 cm). The pulses from the output of the coincidence circuit were recorded by a scaling circuit which measured the intensity of the electron beam and controlled the gate of a type AI-256 pulse-height analyzer to which the pulses from counter C_4 were fed.

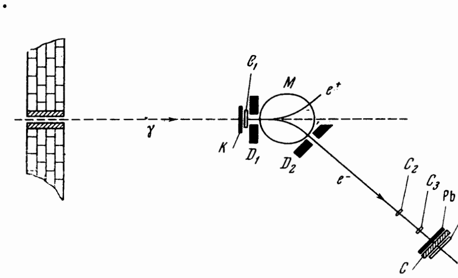

FIG. 1. Experimental arrangement. γ – beam of γ rays; K – lead converter; M – magnet; D_1 and D_2 – lead diaphragms; C_1, C_2, C_3 – scintillation counters which distinguish the electron beam e^-; C_4 scintillation counter spectrometer; Pb – lead absorber; C – graphite absorber.

Measurements of the differential pulse-height spectra from counter C_4 were made for two electron-beam energies E_0 = 115 and 217 MeV. During the measurements the lead absorber thickness t was varied from 0 to 22.7 g/cm^2 Pb, and the graphite absorber thicknesses were t_C = 0, 5.1, and 10.2 g/cm^{2}C, which corresponded to a cutoff energy E of the secondary electron spectrum in the shower of 2, 10, and 20 MeV[10]). The lead and graphite absorbers were placed immediately adjacent to counter C_4. For t_C = 0 the electron path angle accepted by counter C_4 was more than 60°. With increase of t_C this angle decreased to 30°, but this did not lead to an appreciable reduction in the efficiency for detection of shower electrons, since in general the electrons leaving the absorber at large angles have a low energy[11] and are cut off by the absorber.

To avoid errors due to drift of the apparatus (mainly in the spectrometer equipment), we periodically made control measurements of the pulse height spectra for t = 0. The number of showers measured was about 10 000 for the case t = 0 and from 20 000 to 60 000 for t > 0.

3. EXPERIMENTAL RESULTS

Figure 2 shows the distributions $P(E_0, E, t, n)$ of the pulses from counter C_4 as a function of pulse height (analyzer channel number n), measured for E_0 = 217 MeV, t_C = 0, and various values of t. For other values of E_0 and t_C they are similar. For the case t = 0, t_C = 0 the distributions have the characteristic shape of the Landau ionization-loss curve. With increasing t_C the shape of the $P(E_0, E, t = 0, n)$ distributions changes somewhat in the region of large n, which is the result of the interaction of a small fraction of the primary electrons with the material in the graphite absorber.

In the spectra measured for t > 0, several peaks appear distinctly which correspond to simultaneous passage through counter C_4 of one, two, and more shower electrons. For absorber thicknesses t $\gtrsim$ 17 g/cm^2, the flux of electrons of low pulse heights becomes important; this is explained by the appearance in the shower of electrons whose energy is less than 2 MeV—the energy loss of a relativistic electron in counter C_4.

4. ANALYSIS OF RESULTS. DISCUSSION

The measured pulse-height spectra $P(E_0, E, t, n)$ can be represented as linear combinations of distributions $p(N, n)$ corresponding to passage through counter C_4 of N particles (N = 1, 2, ...). If the shower has no angular divergence the function $p(N, n)$ is the fold of N functions $p(N = 1, n) = P(E_0, E, t = 0, n)$:

$$p(N,n)=\int p(1,n_1)p(1,n_2-n_1)\dots p(1,n-n_{N-1})dn_1\dots dn_{N-1}. \quad (1)$$

Angular divergence of the shower electrons leads to an additional displacement of the maximum of the $p(N, n)$ curve and to an increase of its width, which can be taken into account by introduction in (1) of the averaged secant of the electron scattering angle[5]:

$$p(N, n) \to p(N\,\overline{\mathrm{sc}\,\theta}(E_0, E, N, t), n).$$

The experimentally determined pulse-height spectrum $P(E_0, E, t, n)$ is related to the functions $p(N\,\overline{\mathrm{sc}\,\theta}(E_0, E, N, t), n)$ by the relation

$$P(E_0,E,t,n)=\sum_N W_N(E_0,E,t)\,p(N\,\overline{\mathrm{sc}\,\theta}(E_0,E,N,t),n)+f(E_0,E,t,n), \quad (2)$$

where $W_N(E_0, E, t)$ is the probability for production in the shower at a depth t of N electrons with energy grea-

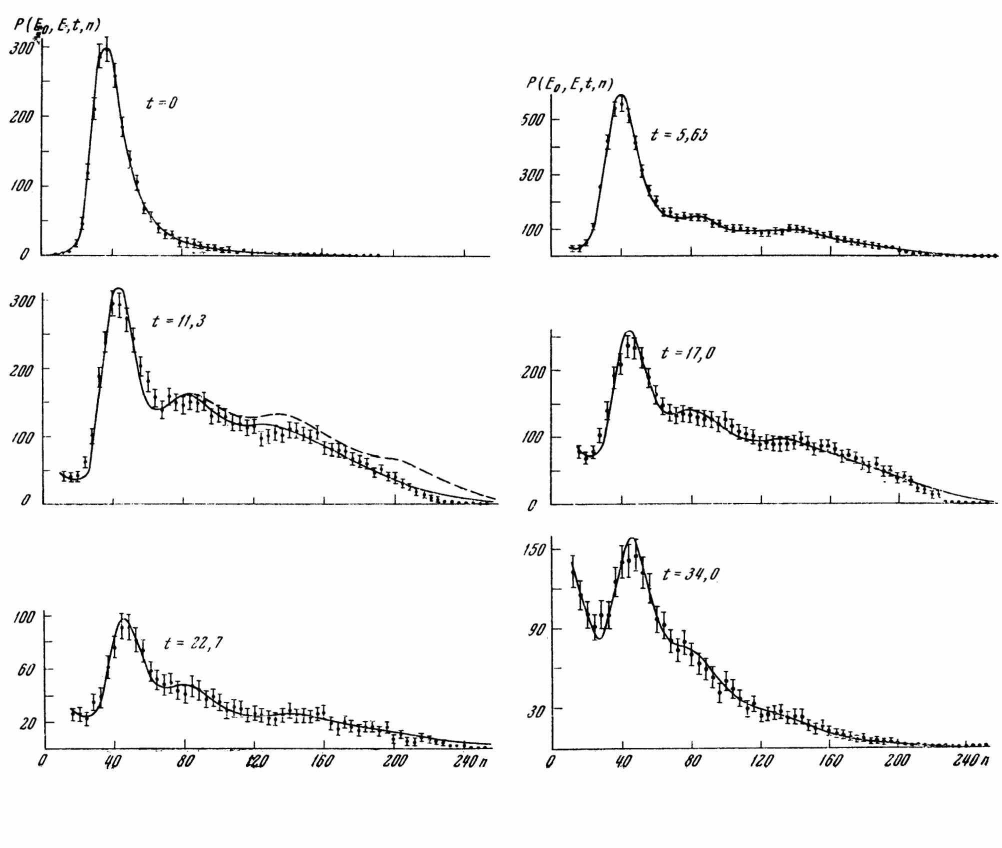

FIG. 2. Pulse height distributions $P(E_0, E, t, n)$ from counter C_4 for E_0 = 217 MeV, t_C = 0 (E = 2 MeV); the dashed line shows the spectrum measured for the case when an additional lead block is placed beyond counter C_4 (backscattering of shower particles). The curves represent Eq. (2) calculated by the method of least squares. Values of t (in g/cm^2 Pb) are indicated in the figure. The analyzer counting rates shown are summed in groups of four channels.

Values of $W_N(E_0, E, t)$ and $\overline{\mathrm{sc}\,\theta}\,(E_0, E, t)$

E_0, MeV	t_C, g/cm²C	E, MeV	t, g/cm²Pb	W_0	W_1	W_2	W_3	$W_{N\geqslant 4}$	$\overline{\mathrm{sc}\,\theta}$
217	0	2	5.65	0.07±0.01	0.56±0.04	0.17±0.02	0.16±0.03	0.04±0.01	1.10±0.03
			11.3	0.19±0.02	0.33±0.03	0.22±0.03	0.17±0.03	0.09±0.02	1.12±0.04
			17.0	0.25±0.02	0.30±0.03	0.21±0.02	0.18±0.02	0.06±0.01	1.16±0.04
			22.7	0.30±0.03	0.33±0.03	0.20±0.02	0.14±0.02	0.03±0.01	1.20±0.05
217	5.1	10	5.65	0.10±0.02	0.55±0.04	0.22±0.03	0.13±0.03	0	1.11±0.03
			11.3	0.20±0.02	0.39±0.03	0.20±0.02	0.18±0.03	0.03±0.01	1.17±0.04
			17.0	0.38±0.03	0.36±0.03	0.16±0.02	0.09±0.02	0.01±0.01	1.20±0.05
			22.7	0.44±0.04	0.37±0.03	0.12±0.02	0.07±0.02	0	1.20±0.06
217	10.2	20	5.65	0.14±0.02	0.60±0.05	0.20±0.02	0.05±0.01	0.01±0.01	1.07±0.04
			11.3	0.30±0.02	0.42±0.03	0.19±0.02	0.09±0.02	0	1.12±0.04
			17.0	0.48±0.03	0.40±0.04	0.07±0.01	0.05±0.02	0	1.15±0.04
			22.7	0.52±0.05	0.41±0.04	0.07±0.02	0	0	1.20±0.06
115	0	2	5.65	0.12±0.02	0.58±0.04	0.16±0.02	0.14±0.03	0	1.12±0.04
			11.3	0.36±0.03	0.32±0.03	0.18±0.03	0.13±0.03	0.01±0.01	1.21±0.05
			17.0	0.50±0.04	0.30±0.03	0.15±0.02	0.05±0.02	0	1.23±0.06
115	5.1	10	5.65	0.19±0.02	0.58±0.05	0.16±0.02	0.07±0.02	0	1.13±0.04
			11.3	0.50±0.03	0.34±0.03	0.11±0.02	0.05±0.02	0	1.18±0.05
			17.0	0.65±0.05	0.26±0.02	0.07±0.02	0.02±0.01	0	1.15±0.06
115	10.2	20	5.65	0.29±0.03	0.60±0.05	0.06±0.02	0.05±0.02	0	1.05±0.04
			11.3	0.61±0.04	0.33±0.03	0.04±0.01	0.02±0.01	0	1.08±0.04
			17.0	0.74±0.04	0.22±0.03	0.03±0.01	0.01±0.01	0	1.10±0.05

ter than E; $f(E_0, E, t, n)$ is the low-energy electron content (see above).

The procedure of analyzing the experimentally obtained spectra $p(E_0, E, t, n)$ was reduced to variation of the quantities $W_N(E_0, E, t)$ and $\overline{\mathrm{sc}\,\theta}\,(E_0, E, N, t)$ and comparison of the calculated and measured spectra. The low-energy electron content $f(E_0, E, t, n)$ was approximated by a linear function of n. The values of $W_N(E_0, E, t)$ found by the method of least squares are presented in the table. Also shown in the table are the average values for a given absorber thickness t of the secant of the shower-electron scattering angle

$$\overline{\mathrm{sc}\,\theta}(E_0, E, t) = \sum_N W_N(E_0, E, t)\,\overline{\mathrm{sc}\,\theta}(E_0, E, N, t). \tag{3}$$

The values of $W_N(E_0, E, t)$ obtained for the cases $t_C = 0$ and $t_C = 5.1$ g/cm²C are in agreement with investigations of fluctuations in showers by means of cloud chambers[5,12] and with Monte Carlo calculations for E = 10 MeV[6] 1). The values of $\overline{\mathrm{sc}\,\theta}\,(E_0, E, t)$ for $t_C = 0$ are close to those obtained from measurement of cloud-chamber photographs.[5] The systematic difference in the results (several per cent) is explained by the fact that values of $\overline{\mathrm{sc}\,\theta}\,(E_0, E, t)$ were determined in ref. 5 by measurement of the tracks of all electrons, including those backscattered from subsequent layers of lead absorber, while in the present work the absorber was placed only in front of the counter and back scattering was absent. When an additional lead absorber was placed beyond counter C_4, the values of $\overline{\mathrm{sc}\,\theta}\,(E_0, E, t)$ increased (Fig. 2) and agreed with those found by the cloud-chamber method.[5]

Figure 3 shows the cascade curves obtained from the measured distributions $P(E_0, E, t, n)$, i.e., the average number of electrons in the shower as a function of depth t,

$$\overline{N}(E_0, E, t) = \sum_N N W_N(E_0, E, t). \tag{4}$$

For $t_C = 0$ they are in good agreement with the cascade curves measured in a cloud chamber.[5] A comparison of the cascade curves obtained for $t_C = 5.1$ g/cm² with the results of a Monte Carlo calculation[6] for the same cutoff energy E = 10 MeV (Fig. 3) also shows good agreement.

In the cascade curves obtained with a Cerenkov counter[3] for E = 10 MeV, the angular divergence of the shower particles was not considered. Therefore they must be compared with the data of the present work before correction for electron scattering. This comparison (Fig. 3) shows some difference in the shapes of the cascade curves. This may be due to the fact that in the Cerenkov-counter experiments the cascade curve was determined approximately[3] as the ratio of the centers of gravity of the spectra.

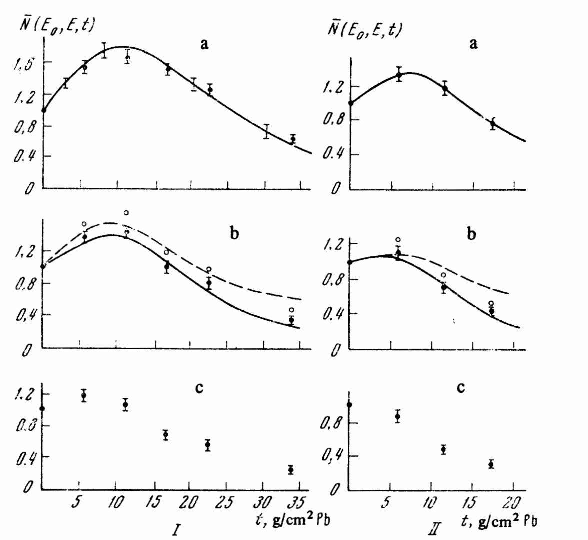

FIG. 3. Cascade curves $N(E_0, E, t)$ for primary electron energies of: I – E_0 = 217 MeV and II – E_0 = 115 MeV. The solid circles are the measured cascade curves (4), and the hollow circles are the same without corrections for angular divergence of the shower particles. a – t_C = 0 (E = 2 MeV), curve – data obtained in a cloud chamber[5]; b – t_C = 5.1 g/cm²C (E = 10 MeV), the solid curve was calculated by the Monte Carlo method [6], and the dashed curve shows the Cerenkov counter measurements [3]; c – t_C = 10.2 g/cm²C (E = 20 MeV).

1)In comparison of the results of the present work with the data of other studies, the latter were interpolated to the values E_0 = 115 and 217 MeV.

5. CONCLUSION

The results obtained in the present work by means of scintillation counters show that this technique makes possible the study of electromagnetic showers at primary electron energies $E_0 \lesssim 1$ BeV (in this case $N < 10$ and the difficulties in the pulse-height analysis are still small) in the region of absorber thickness t up to 5–6 radiation lengths. By this means we can determine such shower characteristics as cascade curves and fluctuations in the number of electrons; in addition, information can be obtained on the angular distribution of the shower electrons. By varying the thickness of the absorber in front of the scintillation counter, it is possible to measure these characteristics for different thresholds of the shower electron spectrum.

Up to the present time a considerable amount of experimental and theoretical information has been accumulated on the development of the electromagnetic cascade in lead. Data on showers in lower Z materials such as copper, iron, and aluminum, which are the main construction materials of track-detecting chambers and are widely used for radiation shielding, are still fragmentary. For a systematic investigation of this little studied field the scintillation counter technique used in the present work can be successfully applied; this method provides a high rate of data collection (particularly for a system of several counters) and the possibility of rapid analysis of the experimental results.

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