Electron-Photon Cascades of High Energy in Photographic Emulsions.

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Recently some electron-photon cascades have been described, which deviate markedly from the results of cascade theory ([1-7]). Moreover, some authors have found the direct production of electron-pairs (tridents) to be more frequent than to be expected from theory ([6-9]). It appears, therefore, to be of great interest to check experimentally the validity of the relations of quantum electrodynamics at high energies upon which some doubts were cast by the experimental results mentioned above.

For this purpose 8 cascades produced by single γ-quanta in emulsions have been systematically investigated up to a shower-depth of at least $t = 1.6$ radiation units (1 radiation unit = 29 mm in emulsion). The energy of each shower particle has been determined by relative multiple scattering measurements made between neighbouring tracks according to standard procedure. The energy loss of the electrons by bremsstrahlung has been taken into account. At high energies (> 100 GeV) the separation of the electron-pairs caused by their scattering ([10]) or the increase in grain-density at the pair origin ([11,15]) has been used to estimate the energy of the pairs.

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In this way it has been found that 6 of the cascades had a total energy (= energy of the producing γ-quanta) of between 20 and 150 GeV (mean energy 50 GeV), and each of the other two cascades an energy of ∼ 300 GeV and ∼ 2 000 GeV respectively.

Shower-development: In Table I the number of shower particles with energies ⩾ 20 MeV is given as a function of the shower-depth for the 6 cascades of energy < 150 GeV. The mean number $\bar{N}$ has been plotted (cf. the points in Fig. 1). To demonstrate the influence of a single cascade on the mean, the mean of only 5 cascades has been taken (crosses), in which the cascade No. 6 has not been taken into account. The drawn curve gives the mean shower development expected from the theory of ARLEY [12]. A good agreement between theory and experiment is to be noted. The same holds also for the energy spectrum (Fig. 2) of the shower particles at various shower depths. The full curves show the theoretical results normalized for the theoretically expected number of shower particles,

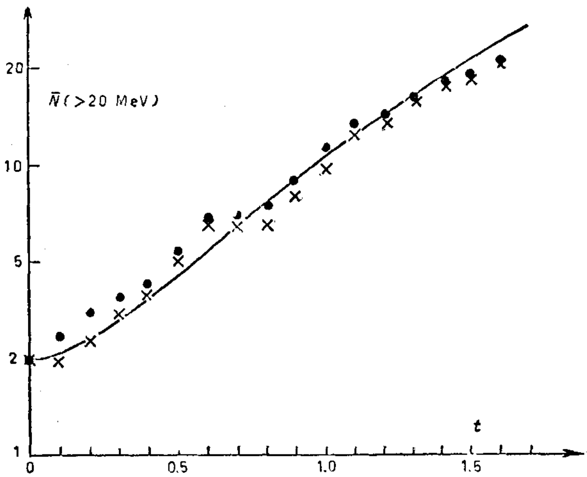

Fig. 1. – The mean number of shower electrons with $E \geqslant 20$ MeV as a function of shower depth t for the 6 cascades given in Tables I and II.

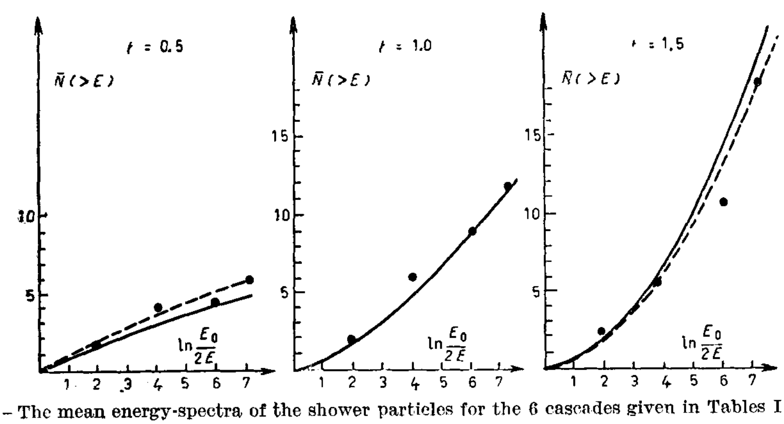

Fig. 2. – The mean energy-spectra of the shower particles for the 6 cascades given in Tables I and II.

TABLE I.

t	Number of cascade						mean $\bar{N}$
	2	3	4	5	6	8	
0	2	2	2	2	2	2	2
0.1	2	2	2	2	4	2	2.33
0.2	2	4	2	2	6	2	3.00
0.3	3	6	2	2	6	2	3.50
0.4	5	6	3	2	6	2	4.00
0.5	5	9	7	2	8	2	5.50
0.6	7	10	7	4	8	4	6.67
0.7	7	10	7	4	10	4	7.00
0.8	8	10	6	4	12	4	7.34
0.9	8	12	8	6	14	6	9.00
1.0	10	14	10	8	18	8	11.33
1.1	12	19	11	11	18	10	13.50
1.2	15	18	13	11	18	10	14.16
1.3	21	20	12	13	20	12	16.33
1.4	25	19	14	14	22	12	17.67
1.5	25	19	14	14	22	15	18.20
1.6	28	23	18	16	24	17	21.00

Number of shower particles with $E \geqslant 20$ MeV as a function of shower depth t. As to the energies of the cascades see Table III.

TABLE II.

No. of pair	Number of cascade					
	2	3	4	5	6	8
1	0	0	0	0	0	0
2	0.285	0.123	0.387	0.595	0.090	0.547
3	0.374	0.299	0.447	0.859	0.123	0.894
4	0.460	0.426	0.447	0.920	0.470	0.966
5	0.523	0.447	0.826	0.977	0.606	1.01
6	0.769	0.530	0.957	1.00	0.738	1.25
7	0.972	0.824	1.06	1.05	0.74	1.47
8	1.02	0.901	1.11	1.29	0.888	1.50
9	1.14	1.05	1.17	1.36	0.955	1.60
10	1.19	1.08	1.25	1.57	0.983	
11	1.24	1.10	1.37		1.105	
12	1.29	1.26	1.37		1.22	
13	1.29	1.58	1.56		1.29	
14	1.33	1.59	1.58		1.29	
15	1.50				1.36	
16	1.50				1.54	
17	1.50					

The shower-depth t of the pairs ($E \geqslant 20$ MeV) created in the 6 cascades with energies between 20 and 150 GeV. As to the energies of the cascades see Table III.

while the dotted curves are normalized for the actually observed number.

In Fig. 3 the mean number of the pairs of energy $\geqslant 20$ MeV created up to a shower depth t has been plotted as a function of t (dotted histogram without cascade No. 6). Fig. 4 shows the energy

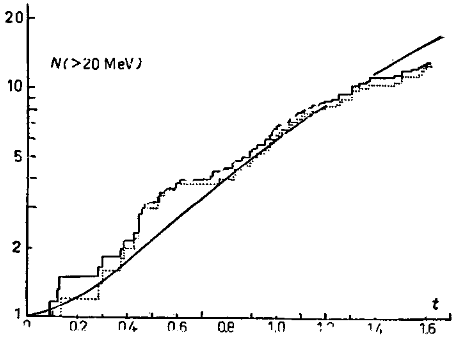

Fig. 3. – The mean number of pairs of energy $\geqslant 20$ MeV created up to a shower depth t as a function of t for the 6 cascades given in Tables I and II.

spectra of these pairs for various values of t. In the figures the full curves give the theoretical results derived from the theory of ARLEY [12].

The deviations from the theoretically predicted number of pairs at $t \geqslant 1.3$ are due to the poor detection efficiency for low energetic pairs at these shower depths, since there the shower particles by Coulomb scattering have already spread to a rather wide distribution in space, and pairs of low energy can be lost. All the other deviations at smaller shower depths may probably be considered as statistical fluctuations.

It is to be noted also that the shower curves and the energy spectra of the two cascades with ~ 300 GeV and ~ 2000 GeV are in agreement with the theoretical predictions (Fig. 5*a*, *b*; 6*a*, *b*).

From these experimental data it can be concluded that the development of the electron-photon cascades up to a total energy of some 1 000 GeV is generally in agreement with cascade theory, and that the theoretical cross-sections for bremsstrahlung and pair-production at high energies apply as well (see also the similar results of K. PINKAU [13]).

Trident-production: The measurement of the m.f.p. of the direct pair-production (tridents) becomes difficult due to bremsstrahlung-pairs (pseudo-tridents), which are produced at so small a distance from the original track that they can be confused with the real tridents within the resolving power of the microscope (< 0.2 μm) [6,8]. In order to make the necessary correction in the number of observed tridents, in the present investigation only the two electrons of the

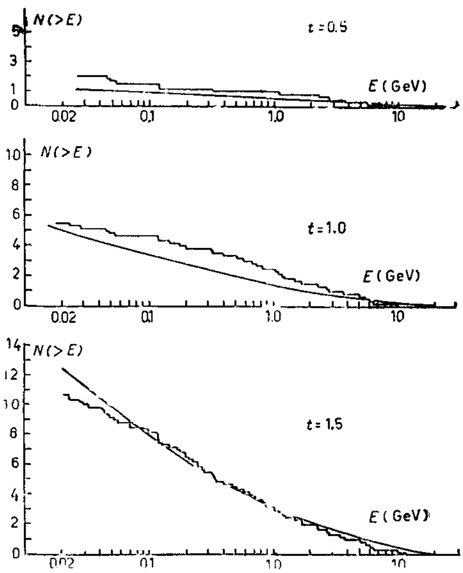

Fig. 4. – The mean energy spectra of pairs created up to a shower depth t for the 6 cascades of Tables I and II.

first pair of each cascade with energy < 150 GeV were used to obtain the m.f.p. of trident production.

The number of pairs of the first generation produced by these 12 primary electron up to $t = 1.0$, is theoretically given as 23.4 (see Table III). Experimentally, one obtains for the total

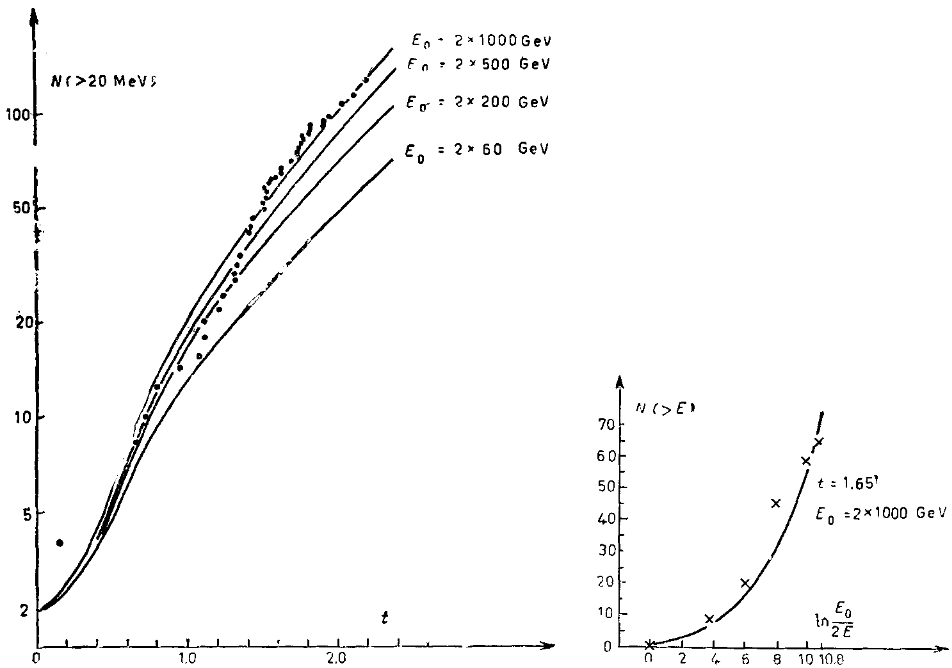

Fig. 5 (*a*, *b*). – The number of shower particles vs. shower depth (*a*) and their energy spectrum (*b*) for a cascade created by a photon with $E_0 \sim 2\,000$ GeV. The drawn curves represent the theoretical predictions, assuming the energies of the electrons of the first pair to be equal.

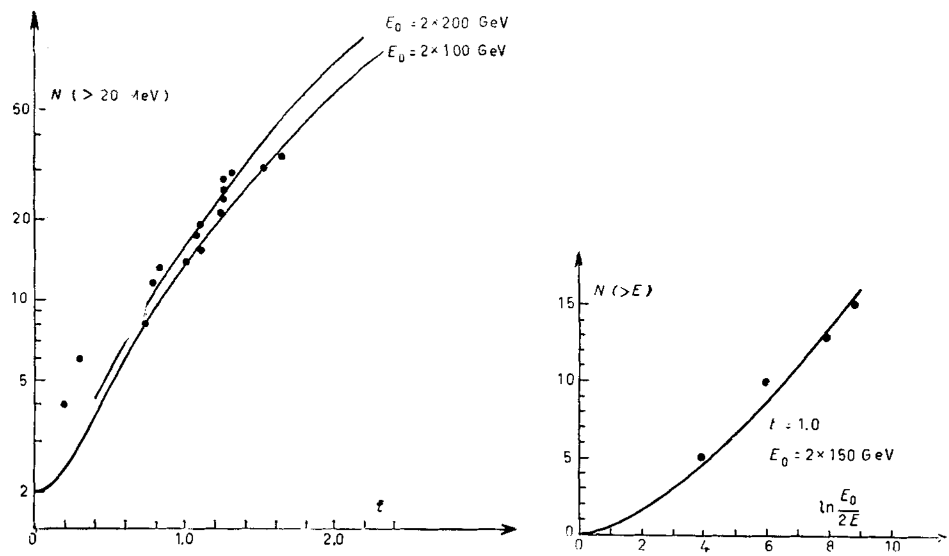

Fig. 6 (*a*, *b*). – The number of shower particles vs. shower depth (*a*) and their energy spectrum (*b*) of a cascade created by a photon with $E_0 \sim 300$ GeV. The drawn curves represent the theoretical predictions, assuming the energies of the electrons of the first pair to be equal.

TABLE III.

1	2	3	4	5	6	7
2	2.5	1.38	0.05	0.069	0.075	0.0364
	30	2.13	0.33	0.703	0.147	0.0863
3	60	2.23	0.46	1.027	0.167	0.1021
	60	2.23	0.46	1.027	0.167	0.1021
4	30	2.13	0.33	0.703	0.147	0.0863
	20	2.01	0.26	0.523	0.133	0.077
5	30	2.13	0.33	0.703	0.147	0.0863
	2.5	1.38	0.05	0.069	0.075	0.0364
6	20	2.01	0.26	0.523	0.133	0.077
	20	2.01	0.26	0.523	0.133	0.077
8	10	1.80	0.17	0.306	0.110	0.0607
	10	1.80	0.17	0.306	0.110	0.0607
		23.42		6.48	1.55	0.89

Evaluation of the number of real tridents.
Meaning of the columns:
1) Number of cascade.
2) Energy of the two primary electrons in GeV.
3) Theoretical number of created pairs of the 1-st generation.
4) Correction-factor according to KOSHIBA *et al.*
5) Number of pseudotridents.
6) Number of real tridents according to the theory of Bhabha.
7) Number of real tridents according to the theory of Racah.

number of the produced pairs up to $t = 1.0$:

	$x < 0.2\ \mu m$;	$x < 5\ \mu m$;
N	7	24
	$x < 10\ \mu m$;	$x < 200\ \mu m$,
N	29	34

where x is the distance of the created pairs from one of the primary electrons. This result is in fair agreement with the theoretical value, if one considers further that to the total number of pairs there is also some contribution from the 2-nd and 3-rd generations.

The number of pseudotridents obtained by means of the correction given by KOSHIBA *et al.* (6) is 6.48 as shown in Table III. Therefore, since the theoretical number of real tridents is 0.89, according to RACAH (14), the total number of real and apparent tridents should be $6.48 + 0.89 = 7.37 \pm 2.7$, which agrees rather well with the value 7 found experimentally.

Our measurements cannot be considered to corroborate the theoretical value due to their low statistical weights However, our experimental value agrees better with the theoretical one than with the experimental findings of other authors (6,9), in which the trident production is greater by at least a factor of 2.5 than to be expected from the theory of BHABHA.

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